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MILITARY HANDBOOK

METALLIC MATERIALS AND ELEMENTS FOR AEROSPACE VEHICLE STRUCTURES

Volume 1 of 2 Volumes

AMSC N/A

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FOREWORD

1. This military handbook is approved for use by all Departments and Agencies of the Department of Defense and the Federal Aviation Administration.

2. Beneficial comments (recommendations, additions, deletions) and any pertinent data which may be of use in improving this document should be addressed to: Chairman, MIL-HDBK-5 Coordination Activity (513-255-5128), WL/MLSE, Wright-Patterson AFB, OH 45433-6533, by using the self-addressed Standardization Document Improvement Proposal (DD Form 1426) appearing at the end of this document or by letter.

3. This document contains design information on the strength properties of metallic materials and elements for aerospace vehicle structures. All information and data contained in this handbook have been coordinated with the Air Force, Army, Navy, Federal Aviation Administration, and industry prior to publication, and are being maintained as a joint effort of the Department of Defense and the Federal Aviation Administration.

Custodians:
Army—AV
Navy—AS
Air Force—11
FAA

Preparing activity:
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Army—ME, MI
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EXPLANATION OF NUMERICAL CODE

For chapters containing materials properties, a deci-numeric system is used to identify sections of text, tables, and illustrations. This system is explained in the examples shown below. Variations of this deci-numerical system are also used in Chapters 1, 8, and 9.

<u>Example A</u>

2.4.2.1.1

General material category (in this case, steel) 2

A logical breakdown of the base material by family characteristics (in this case, intermediate alloy steels); or for element properties 4

Particular alloy to which all data are pertinent. If zero, section contains comments on the family characteristics 2

If zero, section contains comments specific to the alloy; if it is an integer, the number identifies a specific temper or condition (heat treatment) 1

Type of graphical data presented on a given figure (see following description) 1

<u>Example B</u>

3.2.3.1.X

Aluminum 3

2000 Series Wrought Alloy 2

2024 Alloy 3

T3, T351, T3510, T3511, T4, and T42 Tempers 1

Specific Property as Follows X

Tensile properties (ultimate and yield strength)	1
Compressive yield and shear ultimate strengths	2
Bearing properties (ultimate and yield strength)	3
Modulus of elasticity, shear modulus	4
Elongation, total strain at failure, and reduction of area	5
Stress-strain curves, tangent-modulus curves	6
Creep	7
Fatigue	8
Fatigue-Crack Propagation	9
Fracture Toughness	10

CONTENTS-VOLUME 1

NOTE: Information and data for alloys deleted from MIL-HDBK-5 may be obtained from the Chairman, MIL-HDBK-5 Coordination Activity.

CONTENTS-VOLUME 1 (Cont'd)

NOTE: Information and data for alloys deleted from MIL-HDBK-5 may be obtained from the Chariman, MIL-HDBK-5 Coordination Activity.

Chapter 1

GENERAL

1.1 Purpose, Procurement, and Use of Document

1.1.1 INTRODUCTION.—Since many aerospace companies manufacture both commercial and military products, the standardization of metallic materials design data, which are acceptable to Government procuring or certification agencies is very beneficial to those manufacturers as well as governmental agencies. Although the design requirements for military and commercial products may differ greatly, the required design values for the strength of materials and elements and other needed material characteristics are often identical. Therefore this publication is to provide standardized design values and related design information for metallic materials and structural elements used in aerospace structures. The data contained herein or from approved items in the minutes of MIL-HDBK-5 coordination meetings, are acceptable to the Air Force, the Navy, the Army, and the Federal Aviation Administration. Approval by the procuring or certificating agency must be obtained for the use of design values for products not contained herein.

This printed document, distributed by the Naval Publications and Forms Center, is the only official form of MIL-HDBK-5. If computerized MIL-HDBK-5 databases are used, caution should be exercised to ensure that the information in these databases is identical to that contained in this Handbook.

A copy of this Handbook can be requested by phone or by mail. To obtain a copy by phone first obtain a customer order number by dialing (215) 697-2667. Assistance in ordering is also available at this number. After obtaining a customer order number, request a copy of MIL-HDBK-5 by dialing (215) 697-1187 through 1198 or telecopy your order to (215) 697-2978.

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or use DD Form 1425 attached at the end of this chapter and mail to the address indicated on this form.

1.1.2 SCOPE OF DOCUMENT.—This document is intended primarily as a source of design allowables, which are those strength properties of metallic materials and elements (primarily fasteners) that are widely used in the design of aerospace structures. These metallic materials include all systems potentially useful in aerospace and aircraft applications, including those involving reinforcing components. This document also contains information and data for other properties and characteristics, such as fracture toughness strength, fatigue strength, creep strength, rupture strength, fatigue-crack propagation rate, and resistance to stress corrosion cracking. The use of this type of information is not mandatory. Those properties presented as design allowables are listed as A and B, or S-basis values (see Section 1.4.1.1 for definition of basis). Data for other properties are presented as typical. The materials included in this document are standardized with regard to composition and processing methods and are described by industry or government specifications. When needed design allowables are not available in this document, the procuring or certifying government agency should be contacted to determine data requirements and documentation, which may be required to justify design values used by the aerospace company.

In addition to the properties of the materials and elements themselves, there are contained herein some of the more commonly used methods and formulas by which the strengths of various struc-

tural elements or components are calculated. In some cases, the methods presented are empirical and subject to further refinements. Any further expansion of information on element behavior in MIL-HDBK-5 will emphasize those material characteristics needed to assist the design function. Methods of structural analysis are not within the scope of this document.

Where available, applicable references are listed at the end of each chapter. The reference numbers correspond to the paragraph to which they most generally apply. References are provided for guidance to further information on a particular subject, but since data therein may not have met the guidelines criteria of Chapter 9, such material is not to be considered approved by virtue of its listing.

1.1.3 USE OF DESIGN MECHANICAL PROPERTIES.—It is customary to assign minimum values to certain mechanical properties of materials as procurement specification requirements. In the absence of acceptable statistical data, the design mechanical properties given herein are based on these minimum values (see S-Basis in Section 1.4.1.1). The manner in which these design mechanical properties are to be used will depend on the type of structure being considered and will be specified in the detailed structural requirements of the procuring or certificating agency. The use of the different design mechanical properties, such as ultimate tensile strength, yield strength, etc.; the factors of safety associated with them; and the arbitrary reductions in allowable stresses (which may be in the nature of specific requirements, or may be considered necessary in particular cases); will not be taken up in detail since information of this sort does not affect the material properties as such.

1.2 Symbols, Abbreviations, and Systems of Units

1.2.1 SYMBOLS AND ABBREVIATIONS.—The symbols and abbreviations used in this document are defined in this section with the exception of statistical symbols. These latter symbols are defined in Chapter 9.

A	Area of cross section, square inches; ratio of alternating stress to mean stress; subscript "axial"; A basis for mechanical-property values (see Section 1.4.1.1)
AISI	American Iron and Steel Institute
AMS	Aerospace Materials Specification (published by Society of Automotive Engineers, Inc.)
AN	Air Force-Navy Aeronautical Standard
Ann	Annealed
ASTM	American Society for Testing and Materials
a	Amplitude; crack or flaw dimension
a_c	Critical half crack length
a_o	Initial half crack length
B	Biaxial ratio (see Equation 1.3.2.8); B basis for mechanical-property values (see Section 1.4.1.1)
Btu	British thermal unit(s)
BUS	Individual or typical bearing ultimate strength
BYS	Individual or typical bearing yield strength
b	Width of sections; subscript "bending"
br	Subscript "bearing"
C	Specific heat; Celsius; Constant
CC	Center cracked
CEM	Consumable electrode melted
CRES	Corrosion resistant steel (stainless steel)
CT	Compact tension
CYS	Individual or typical compressive yield strength
c	Fixity coefficient for columns; subscript "compression"

cpm	Cycles per minute
D	Diameter; hole or fastener diameter; dimpled hole
d	Mathematical operator denoting differential
E	Modulus of elasticity in tension; average ratio of stress to strain for stress below proportional limit
E_c	Modulus of elasticity in compression; average ratio of stress to strain below proportional limit
E_s	Secant modulus of elasticity
E_t	Tangent modulus of elasticity
e	Elongation in percent, a measure of the ductility of a material based on a tension test; unit deformation or strain; subscript "fatigue or endurance"; the minimum distance from a hole center to the edge of the sheet
e_e	Elastic strain
e_p	Plastic strain
e/D	Ratio of edge distance to hole diameter (bearing strength)
ELI	Extra low interstitial (grade of titanium alloy)
ER	Equivalent round
ESR	Electro-slag remelted
F	Allowable stress; Fahrenheit
F_A	Axial stress
F_b	Allowable bending stress; modulus of rupture in bending
F_{bru}	Allowable ultimate bearing stress
F_{bry}	Allowable bearing yield stress
F_c	Allowable column stress
F_{cc}	Allowable crushing or crippling stress (upper limit of column stress for local failure)
F_{cu}	Ultimate compressive stress
F_{cy}	Allowable compressive yield stress at which permanent strain equals 0.002
F_H	Hoop stress
F_s	Allowable shear stress
F_{sp}	Proportional limit in shear
F_{st}	Modulus of rupture in torsion
F_{su}	Allowable ultimate stress in pure shear (this value represents the average shear stress over the cross section)
F_{tp}	Proportional limit in tension
F_{tu}	Allowable tensile stress
F_{ty}	Allowable tensile yield stress at which permanent strain equals 0.002
f	Internal (or calculated) stress; stress applied to the gross flawed section; creep stress
f_b	Internal (or calculated) primary bending stress
f_c	Internal (or calculated) compressive stress; maximum stress at fracture: gross stress limit (for screening elastic fracture data)
f_{pl}	Plastic stress
f_s	Internal (or calculated) shear stress
f_t	Internal (or calculated) tensile stress
ft	Foot: feet
G	Modulus of rigidity (shear modulus)
Gpa	Gigapascal(s)
g	Gram(s)
H	Subscript "hoop"
hr	Hour(s)
I	Moment of inertia
i	Slope (due to bending) of neutral plane of a beam, in radians (1 radian = 57.3 degrees)
in.	Inch(es)
J	Torsion constant (= Ip for round tubes); Joule

K	A constant, generally empirical; thermal conductivity; stress intensity; Kelvin; correction factor
K_{app}	Apparent plane stress fracture toughness or residual strength
K_c	Critical plane stress fracture toughness, a measure of fracture toughness at point of crack growth instability
K_{Ic}	Plane strain fracture toughness
K_N	Empirically calculated fatigue notch factor
K_t	Theoretical elastic stress concentration factor
k	Strain at unit stress
ksi	Kips (1,000 pounds) per square inch
L	Length; subscript "lateral"; longitudinal (grain direction)
LT	Long transverse (grain direction)
lb	Pound
M	Applied moment or couple, usually a bending moment
Mc	Machine countersunk
Mg	Megagram(s)
MIG	Metal-inert-gas (welding)
MPa	Megapascal(s)
MS	Military Standard
M.S.	Margin of safety
m	Subscript "mean"; metre; slope
mm	Millimetre(s)
N	Fatigue cycles to failure; Newton; normalized
NAS	National Aerospace Standard
n	Subscript "normal"; cycles applied to failure; shape parameter for the standard stress-strain curve (Ramberg-Osgood parameter); number of fatigue cycles endured
P	Applied load (total, not unit, load); exposure parameter; probability
Pu	Test ultimate load, pounds per fastener
Py	Test yield load, pounds per fastener
p	Subscript "polar"; subscript "proportional limit"
psi	Pounds per square inch
Q	Static moment of a cross section
Q&T	Quenched and tempered
R	Stress ratio, ratio of minimum stress to maximum stress in a fatigue cycle; reduced ratio
R_b	Stress ratio in bending
R_c	Stress ratio in compression; Rockwell hardness - C scale
R_s	Stress ratio in shear or torsion; ratio of applied load to allowable shear load
R_t	Ratio of applied load to allowable tension load
R.H.	Relative humidity
RA	Reduction of area
RMS	Root-mean-square (surface finish)
RT	Room temperature
r	Radius; root radius; reduced ratio (regression analysis)
S	Shear force; nominal stress, fatigue; S basis for mechanical-property values (see Section 1.4.1.1)
S_a	Stress amplitude, fatigue
S_e	Fatigue limit
S_m	Mean stress, fatigue
S_{max}	Highest algebraic value of stress in the stress cycle
S_{min}	Lowest algebraic value of stress in the stress cycle
S_r	Algebraic difference between the maximum and minimum stresses in one cycle
SAE	Society of Automotive Engineers

SCC	Stress-corrosion cracking
ST	Short transverse (grain direction)
STA	Solution treated and aged
SUS	Individual or typical shear ultimate strength
SYS	Individual or typical shear yield strength
s	Subscript "shear"
S/N	S = stress; N = number of cycles
T	Applied torsional moment; transverse (grain direction); subscript "transverse"
TIG	Tungsten-inert-gas (welding)
TUS	Individual or typical tensile ultimate strength
TYS	Individual or typical tensile yield strength
T_F	Exposure temperature
t	Thickness; subscript "tension"; exposure time; elapsed time
U	Factor of utilization
u	Subscript "ultimate"
W	Width of center-through-cracked tension panel; Watt
x	Distance along a coordinate axis
Y	Nondimensional factor relating component geometry and flaw size
y	Deflection (due to bending) of elastic curve of a beam; distance from neutral axis to given fiber; subscript "yield"; distance along a coordinate axis
Z	Section modulus, I/y
z	Distance along a coordinate axis
α	Coefficient of thermal expansion, mean; constant
β	Constant
δ	Deflection
ε_t	Total (elastic plus plastic) strain at failure determined from tensile stress-strain curve
Φ	Angular deflection
ρ	Radius of gyration; Neubur constant (block length)
μ	Poisson's ratio
ω	Density; flank angle
∞	Infinity

1.2.2 INTERNATIONAL SYSTEMS OF UNITS (SI).—The design allowables listed in MIL-HDBK-5 are given in customary units of U.S. measure to insure compatibility with government and industry material specifications and current aerospace design practice. Table 1.2.2 may be used to assist in the conversion of these units to SI units when desired. Prefixes for the SI units shown in this table were selected to give the same number of significant figures as are currently used in MIL-HDBK-5.

TABLE 1.2.2 *Conversion of U.S. Units of Measure Used in MIL-HDBK-5 to SI Units*

Quantity or Property	To Convert From U. S. Unit	Multiply by[a]	SI Unit[b]
Area	in.^{2}	645.16[c]	Millimetre^2 (mm^2)
Force	lb	4.4482	Newton (N)
Length	in.	25.4[c]	Millimetre (mm)
Stress	ksi	6.895	Megapascal (MPa)[d]
Stress intensity factor	ksi $\sqrt{\text{in.}}$	1.0989	Megapascal $\sqrt{\text{metre}}$ (MPa $\cdot$ m$^{1/2}$)[d]
Modulus	10^3 ksi	6.895	Gigapascal (GPa)[d]
Temperature	°F	$\frac{F + 459.67}{1.8}$	Kelvin (K)
Density (ω)	lb/in.^{3}	27.680	Megagram/metre^3 (Mg/m^3)
Specific heat (C)	Btu/lb·F (or Btu·lb^{-1}·F^{-1})	4.1868[c]	Joule/(gram·Kelvin) (J/g·K) or J·g^{-1} ·K^{-1})
Thermal conductivity (K)	Btu/[(hr)(ft^2)(F)/ft] (or Btu·hr^{-1}·ft^{-2}·F^{-1}·ft)	1.7307	Watt/(metre·Kelvin) W/(m·K) or W·m^{-1}·K^{-1})
Thermal expansion (α)	in./in./F (or in.·in.$^{-1}$·F^{-1})	1.8	Metre/metre/Kelvin m/(m·K) or (m·m^{-1}·K^{-1})

[a] Conversion factors to give significant figures are as specified in ASTM E 380, NASA SP-7012, second revision. NBS Special Publication 330, and *Metals Engineering Quarterly*.

[b]

Prefix	Multiple	Prefix	Multiple
giga (G)	10^9	milli (m)	10^{-3}
mega (M)	10^6	micro (μ)	10^{-6}
kilo (k)	10^3		

[c] Conversion factor is exact.

[d] One Pascal (Pa) = one Newton/metre^2.

1.3 Commonly Used Formulas

1.3.1 GENERAL.—The formulas in the following sections are listed for reference purposes. The sign conventions generally accepted in their use are that quantities associated with tensile action (load, stress, strain, etc.) are considered as positive, and quantities associated with compressive action are considered as negative. When compressive action is of primary interest, however, it is sometimes convenient to consider the associated quantities to be positive. Formulas for statistical computations to obtain design allowables are presented in Chapter 9.

1.3.2 SIMPLE UNIT STRESSES

1.3.2.1 f_t = P/A (tension)
1.3.2.2 f_c = P/A (compression)
1.3.2.3 f_b = My/I = M/Z
1.3.2.4 f_s = S/A (average direct shear stress)
1.3.2.5 f_s = SQ/Ib (longitudinal or transverse shear stress)
1.3.2.6 f_s = Ty/Ip (shear stress in round tubes due to torsion)
1.3.2.7 f_s = T/2 At (shear stress due to torsion in thin-walled structures of closed section; note that A is the area enclosed by the median line of the section)
1.3.2.8 $f_A = Bf_H$; $f_T = Bf_L$

1.3.3 COMBINED STRESSES (See Section 1.5.3.5)

1.3.3.1 $f_A = f_c + f_b$ (compression and bending)

1.3.3.2 $f_{smax} = \left(\left(f_s^2\right) + \left(f_n/2\right)^2\right)^{1/2}$ (compression, bending, and torsion)
1.3.3.3 $f_{nmax} = (f_n/2) + f_{smax}$

1.3.4 DEFLECTIONS (AXIAL)

1.3.4.1 e = δ/L (unit deformation or strain)
1.3.4.2 E = f/e (This equation applies when E is to be found from tests in which f and e are measured.)
1.3.4.3 δ = eL = (f/E)L
= PL/AE (This equation applies when the deflection is to be calculated using a known value of E.)

1.3.5 DEFLECTIONS (BENDING)

1.3.5.1 di/dx = M/EI (change of slope per unit length of beam, radians per unit length)

1.3.5.2 $i_2 = i_1 + \int_{x_1}^{x_2} (MT/EI)\,dx$ — slope at Point 2. (The integral denotes the area under the curve of M/EI plotted against x, between the limits of x_1 and x_2.)

1.3.5.3 $y_2 = y_1 + i_1 (x_2 - x_1) + (M/EI) \int_{x_1}^{x_2} (x_2 - x)\,dx$ — deflection at Point 2. (The integral denotes the area under the curve having ordinates equal to M/EI multiplied by the corresponding distances to Point 2, plotted against x, between the limits of x_1 and x_2.)

1.3.5.3(a) $y_2 = \int_{x_1}^{x_2} i\,dx$ — deflection at Point 2. (The integral denotes the area under the curve of $x_1(i)$ plotted against x, between the limits x_1 and x_2.)

1.3.6 DEFLECTION (TORSION)

1.3.6.1 $d\Phi/dx = T/GJ$ (change of angular deflection of twist per unit length of member, radians per unit length)

1.3.6.2 $\Phi = \int_{x_1}^{x_2} (T/GJ)\,dx$ = total twist over a length from x_1 to x_2. (The integral denotes the area under the curve of T/GJ plotted against x, between the limits of x_1 and x_2.)

1.3.6.2(a) $\Phi = TL/GJ$ (used when torque T/GJ is constant over length L)

1.3.7 BIAXIAL ELASTIC DEFORMATION

1.3.7.1 $\mu = \dfrac{\text{unit lateral deformation}}{\text{unit axial deformation}}$ (Poisson's ratio in uniaxial loading)

1.3.7.2 $Ee_x = f_x - \mu f_y$

1.3.7.3 $Ee_y = f_y - \mu f_x$

1.3.7.4 $E_{biaxial} = E/(1-\mu B)$ (biaxial elastic modulus)

1.3.8 BASIC COLUMN FORMULA

$$F_c = \pi^2 E_t/(L'/\rho)^2 \text{ where } L' = L\sqrt{c}$$

1.4 Basic Principles and Definitions

1.4.1 GENERAL.—It is assumed that engineers using this document are thoroughly familiar with the basic principles of strength of materials. A brief summary of such material is presented here for the sake of uniformity and to emphasize certain principles of special importance. The design mechanical-property values of various metals and elements are provided in the tables in each chapter.

As a means of maintaining uniformity in the presentation of mechanical-property values in this document and a high level of assurance in the values reported, statistical techniques are employed where possible and requirements have been established to insure adequacy of supporting data and description of the product represented by the mechanical-property values.

1.4.1.1 *Basis.*—Primary strength properties (F_{tu}, F_{ty}, F_{cy}, F_{su}, F_{bru} and F_{bry}) presented in the design mechanical-property tables are minimum values at room temperature, established on an A, B, or S basis, as defined below. Properties at other temperatures, when determined in accordance with Section 1.4.1.3, shall be regarded as having the same basis as the corresponding room-temperature values.

Elongation and reduction of area properties listed in the design mechanical-property tables are minimum values at room temperature and are presented on an S basis only. Elongation and reduction in area at other temperatures, as well as elastic properties (E, E_c, G, and μ), physical properties (ω, C, K, and α), creep properties, fatigue properties, and fracture toughness properties shall be regarded as typical values unless a basis is specifically indicated.

A-Basis.—At least 99 percent of the population of values is expected to equal or exceed the A basis mechanical property allowable, with a confidence of 95 percent.

B-Basis.—At least 90 percent of the population of values is expected to equal or exceed the B basis mechanical property allowable, with a confidence of 95 percent.

S-Basis.—The S-value is the minimum value specified by the governing industry specification (as issued by industry standardization groups such as SAE Aerospace Materials Division, ASTM, etc.) or federal or military standards for the material. (See MIL-STD-970 for order of preference for specifications.) For certain products heat treated by the user (for example, steels hardened and tempered to a designated F_{tu}), the S-value may reflect a specified quality-control requirement. Statistical assurance associated with this value is not known.

Typical Basis.—The typical property value is an average value and has no statistical assurance associated with it.

Use of B-Values.—The use of B-values is permitted in design by the Air Force, Navy, and Federal Aviation Administration, subject to certain limitations as specified by each agency. Reference should be made to specific requirements of the applicable agency before using the B-values in design.

1.4.1.2 *Directly Calculated Values.*—Directly calculated values having an A-basis are equal to $x - ks_x$ where k is $k_{0.99,0.95,n}$ (where 0.99 = probability, 0.95 = confidence, and n = number of measurements). Those having a B-basis are equal to $x - ks_x$ where k is $k_{0.90,0.95,n}$. These formulas assume that the distribution of mechanical-property values is normal. See Section 9.2.7 for further details.

Where there is evidence of an inherent distribution other than normal, the three-parameter Weibull or nonparametric analysis is used to approximate this same degree of assurance. See Sections 9.2.8 and 9.2.9.

When a property varies continuously with thickness, regression analysis is used. See Section 9.2.11.

Data requirements for establishing allowables in this manner must be adequate to represent the current process capability of a material. Normally, a minimum of 100 individual measurements are required. These contain data from at least 10 production heats from a majority of the major producers of the material. If possible, tests conducted by more than one source are included. These requirements apply to each significant variable, such as form, heat-treated condition or temper, size or thickness range, and testing direction, that may affect the distribution of properties.

1.4.1.3 *Derived Values.*—A derived value is a mechanical property that is determined through its relationship to an established property. A derived property may be a tensile strength in a different grain direction from the established direction, or it may be another strength property (compression, shear, or bearing), or it may be the same strength property at a different temperature. See Section 9.2.10.

Derived values are presented in tabular form in stress units in design mechanical properties tables or in graphical form in percentage units of the room temperature strength property. Tabular values will have both their dimensional units and data basis indicated. These values represent the product of a reduced ratio and the value of an established primary strength property.

Percentages selected from effect-of-temperature curves represent reduced ratios of the property-at-temperature to the room-temperature value for that property. The product of a percentage and the room-temperature value for a property shall be regarded as yielding a property-at-temperature value having the same basis as that indicated for the room-temperature value for the property. Unless otherwise indicated, the percentage curves for these properties apply to all forms and thicknesses shown in the design mechanical property table for the temper indicated. Normally, these curves represent materials exposed at testing temperatures for times up to one-half hour and strained at the rate specified for the individual property. When data are adequate, curves for

other exposure times are also presented and are labeled appropriately. See Section 9.3.1.

1.4.2 STRESS

1.4.2.1 *General.*—The term "stress" as used herein always implies a force per unit area and is a measure of the intensity of the force acting on a definite plane passing through a given point (see Equations 1.3.3.1 and 1.3.2.2). The stress distribution may or may not be uniform, depending on the nature of the loading condition. For example, tensile stresses as found from Equation 1.3.2.1 are considered to be uniform. The bending stress determined from Equation 1.3.2.3 refers to the stress at a point located at a distance y from the neutral axis. The shear stress over the cross section of a member subjected to bending is not uniform. (Equation 1.3.2.4 gives the average shear stress.)

1.4.2.2 *Normal, Shear, and Principal Stresses.*—The stresses acting at a point in any stressed member can be resolved into components acting on planes through the point.

The normal and shear stresses acting on any particular plane are the stress components perpendicular and parallel, respectively, to the plane. A simple conception of these stresses is that normal stresses tend to pull apart (tensile stresses) or press together (compressive stresses) adjacent particles of the material, whereas shear stresses tend to cause such particles to slide on each other. Tensile stresses are denoted arbitrarily (+) stresses and compressive stresses are called negative (-) stresses.

If one selects three mutually perpendicular planes through a point, there is always some orientation of this system such that only normal stresses exist, all other stresses being zero. These normal stresses are known as principal stresses, and the numerically largest of these is called the maximum principal stress.

1.4.2.3 *State of Stress.*—A triaxial stress state is defined as one in which there are three principal stresses, none of which is equal to zero. When one of the principal stresses is equal to zero, the stress state is called biaxial. When two of the principal stresses are equal to zero, uniaxial state of stress is said to exist.

1.4.3 STRAIN

1.4.3.1 *General.*—Strain is the change in length per unit length in a member or portion of a member. As in the case of stress, the strain distribution may or may not be uniform in a complex structural element, depending on the nature of the loading condition. Strains usually are present also in directions other than the direction or directions of the applied stresses.

1.4.3.2 *Normal and Principal Strains; Poisson's Ratio.*—A normal strain is that strain that is associated with a normal stress; a normal strain takes place in the direction in which its associated normal stress acts. Normal strains that result from an increase in length are denoted arbitrarily as positive (+) strains and those that result from a decrease in length are called negative (-) strains.

If one selects three mutually perpendicular planes through a point, there is always some orientation of this system such that only normal strains exist, all shear strains being zero. These normal strains are known as principal strains. The direction of the principal strains coincides with the direction of the principal stresses only for isotropic materials.

In uniaxial loading, strain in the direction of the applied stress varies with that stress. The ratio of stress to strain has a constant value (E) within the elastic range of a material but decreases when plastic strain is encountered. The axial strain is always accompanied by lateral strains of opposite sign in the two directions mutually perpendicular to the axial strain. Under uniaxial conditions, the absolute value of the ratio of either of the lateral strains to the axial strain is called Poisson's ratio. For stresses within the elastic range, this ratio is approximately constant. For stresses beyond the elastic limit, this ratio is a function of the axial strain and is then sometimes called the lateral contraction ratio. Information on the variation of Poisson's ratio with strain and with testing direction is available in Reference 1.4.3.2.

In multiaxial loading, the strains resulting from the application of each of the stresses are additive; thus, the strains in each of the principal directions must be calculated, taking into account each of the principal stresses and Poisson's ratio (see Equations 1.3.7.2 and 1.3.7.3 for biaxial loading).

1.4.3.3 *Shear Strain.*—If an element of uniform thickness is subjected to pure shear, there will be a displacement of each side of the clement relative to the opposite side. The shear strain is obtained by dividing this displacement by the distance between the sides of the element. It should be noted that shear strain is obtained by dividing a displacement by a distance at right angles to the displacement, whereas axial strain is obtained by dividing the deformation by a length measured in the same direction as the deformation.

1.4.3.4 *Strain Rate.*—Loads on structures will result in conditions ranging from those where strains are constant to those where strains are rapidly changing. The stress-strain curve, ultimate tensile strength, and ductility of some materials are affected by changes in the rate of strain. For this reason, where available, statements or data relative to strain-rate effects are provided in connection with specific metals. These data apply only up to the value stated or to a rate of 1 percent per second, which is considered the maximum rate likely to occur in aircraft or missile structures except for nuclear effects. Unless otherwise stated for specific materials, strain rates can be assumed to have been between 0.001- and 0.01-inch per inch per minute to the yield strength. After yield strength was reached, the speed of testing can be assumed to have been increased to a rate, which did not exceed 0.5-inch per inch of gage length per minute to failure (ultimate strength). Property variations within this range of strain rate are considered too small to necessitate consideration in design. Most of the strain rates used to determine yield strength were between 0.003- and 0.007-inch per inch per minute.

1.4.3.5 *Elongation and Reduction of Area.*—Elongation and reduction of area are measured in accordance with specification ASTM E 8.

1.4.4 TENSILE PROPERTIES

1.4.4.1 *General.*—When a specimen of a certain material is tested in tension using the standard testing procedures in ASTM E 8, it is customary to plot the results of such a test as a "stress-strain diagram". Typical tensile diagrams, not to scale, are shown in Figure 1.4.4.1. Typical

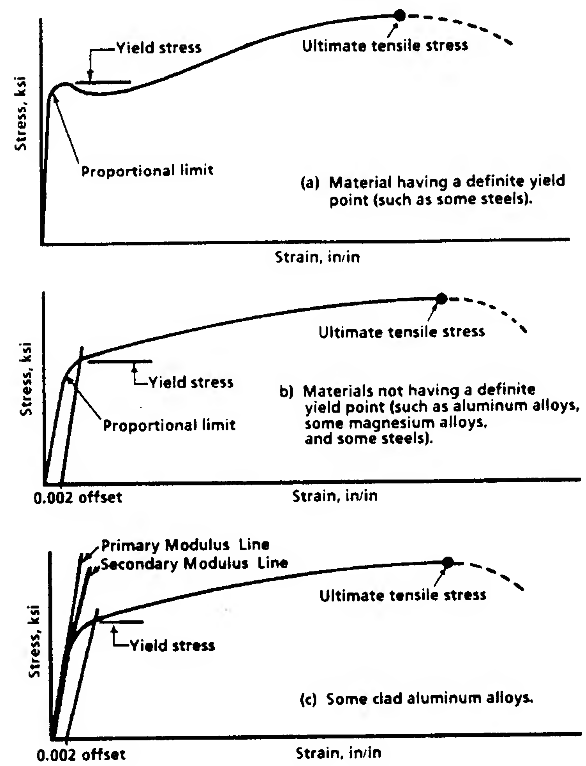

FIGURE 1.4.4.1 *Typical tensile stress-strain diagrams.*

stress-strain diagrams drawn to scale appear in appropriate chapters for the general information of the users of this document. These diagrams have been adjusted in such a manner that the slopes of the straight-line portions of the curves are equal to the elastic modulus values reported elsewhere for the specific material. It should be noted that the strain scale is nondimensional, whereas the stress scale is in pounds per square inch. The important mechanical properties, which can be shown in the stress-strain diagram are discussed in Sections 1.4.4.2 to 1.4.4.7.

1.4.4.2 *Modulus of Elasticity (E).*—Referring to Figure 1.4.4.1, it will be noted that the first part of the diagram is typically a straight line. This indicates a constant ratio between stress and strain

over that range. The numerical value of the ratio is called the "modulus of elasticity", denoted by E. It will be noted that E is the slope of the straight portion of the stress-strain diagram and is determined by dividing the stress (in pounds per square inch) by the strain (which is nondimensional). See Equation 1.3.4.2. Therefore, E has the same dimensions as stress; in this case, pounds per square inch.

Other moduli that are often of interest are the tangent modulus, E_t, and the secant modulus; E_s, E_t, and E_s change with stress above the proportional limit. The tangent modulus for a particular stress is the slope of the stress-strain diagram at a point corresponding to that stress, and the corresponding secant modulus is the slope of a line drawn through the origin and a point on the diagram at the same stress.

Clad aluminum alloys may have two separate modulus values, as indicated in the typical curve presented in Figure 1.4.4.1. The initial, or primary, modulus is typically an average of the elastic moduli of the core and cladding, and it applies only up to the proportional limit of the cladding. For example, the primary modulus of 2024-T3 clad sheet applies only up to about 6 ksi. Similarly, the primary modulus of 7075-T6 clad sheet applies only up to approximately 12 ksi. A typical use of primary moduli is for low amplitude, high frequency fatigue. However, primary moduli should not be used for general stress analysis or structural design. Immediately above this point there is a short transition range, and the material then exhibits a secondary modulus up to the proportional limit of the core material. This secondary modulus is the slope of the second straight-line portion of the diagram. In some cases, the cladding is so little different from the core that a single modulus value is used.

1.4.4.3 *Tensile Proportional Limit (F_{tp})*.—The tensile proportional limit is the maximum stress in which strain remains directly proportional to stress. Since it is practically impossible to determine precisely this point on a stress-strain diagram, it is customary to assign a small value of permanent strain and identify the corresponding stress value (at the intersection with the stress strain curve) as the proportional limit. The selected permanent strain offset value should be stated when using the proportional limit.

1.4.4.4 *Tensile Yield Stress (F_{ty})*.—The stress-strain diagrams for some steels show a sharp break at a stress below the ultimate tensile stress. At this critical stress, the material elongates considerably with no increase in stress (see Figure 1.4.4.1). The stress at which this takes place is referred to as the yield point. Most nonferrous metals and most high strength steels do not show this sharp break, but yield more gradually so that there is no yield point. This condition is illustrated in Figure 1.4.4.1. Since permanent deformations of any appreciable amount are undesirable in most structures, it is customary to adopt an arbitrary amount of permanent strain that is considered admissible for general purposes. The value of this strain has been established by material testing engineers as 0.002m and the corresponding stress is called the yield stress. For practical purposes, this may be determined from the stress-strain diagram by drawing a line parallel to the straight (or elastic) portion of the curve through a point representing zero stress and 0.002 strain (see Figure 1.4.4.1). The yield stress is taken as the stress at the intersection of this straight line with the stress-strain curve.

1.4.4.5 *Ultimate Tensile Stress (F_{tu})*.—Figure 1.4.4.1 shows how the ultimate tensile stress is determined from the stress-strain diagram. It is simply the stress at the maximum load reached in the test. It should be noted that all stresses are based on the original cross-sectional area of the test specimen, without regard to the lateral contraction of the specimen, which actually occurs during the test. The ultimate tensile stress is commonly used as a criterion of the strength of the material for structural application, but it should be kept in mind that other strength properties may often be more important.

1.4.4.6 *Elongation (e)*.—An additional property that is determined from the tensile test is elongation, which is a measure of ductility. Elongation is the increase in gage length, measured after fracture of the tensile specimen within the gage length, expressed as a percentage of the original gage length. Elongation is usually measured in 2 inches for rectangular tensile specimens and in 4D for round specimens, except welded

specimens. See applicable material specification for specified gage length. Although tensile elongation is widely used as an indicator of ductility, the measurement can be significantly affected by testing variables, such as thickness and gage length of the test specimen. See Section 1.4.1.1 for data basis.

1.4.4.7 *Reduction of Area (RA).*—Another property determined from the tensile test is reduction of area, which is also a measure of ductility. Reduction of area is the difference, expressed as a percentage of original area, between the original cross sectional area of the tensile test specimen and the minimum cross-sectional area measured after fracture of the tensile specimen. The reduction of area measurement is less affected by testing variables than the elongation measurement, but it is more difficult to use on products having thin sections. See Section 1.4.1.1 for data basis.

1.4.5 COMPRESSIVE PROPERTIES

1.4.5.1 *General.*—The results of compression tests can be plotted as stress-strain diagrams similar to those shown in Figure 1.4.4.1 for tension. The preceding remarks (with the exception of those pertaining to ultimate stress and tensile proportional limit) concerning the specific tensile properties of the material apply in a similar manner to the compressive properties. It should be noted that the moduli of elasticity in tension and compression are approximately equal (or slightly greater in compression) for most of the commonly used structural materials. Special considerations concerning the ultimate compressive stress are taken up in the following section. An evaluation of techniques of obtaining compressive strength properties of thin sheet material is outlined in Reference 1.4.5.1.

1.4.5.2 *Ultimate Compressive Stress (F_{cu}).*—It is difficult to discuss this property without reference to column action. Almost any piece of material, unless very short, tends to buckle laterally as a column under compressive loadings, and the load at failure usually depends on the relation of the length of the piece to its cross-sectional dimensions. Column failure cannot occur, however, when a piece is very short in comparison with its cross-sectional dimensions, or when it is restrained laterally by external means. Under these conditions, some materials such as stone, wood, and a few metals, will fail by fracture, thus giving a definite value for the ultimate compressive stress. Most metals, however, are so ductile that no fracture is encountered in compression. Instead of fracturing, the material yields and swells out, so that the increasing area continues to support the increasing load. It is almost impossible to select a value for the ultimate compressive stress of such materials without having some arbitrary criterion. For wrought metals, it is common practice to assume that the ultimate compressive stress is equal to the ultimate tensile stress. For some cast metals, which are relatively weak in tension, an ultimate tensile stress may be obtained from tests on short compact specimens. When tests are made on such specimens having an L'/ρ approximately equal to 12, the ultimate stress obtained is called the block compressive stress.

1.4.6 SHEAR PROPERTIES

1.4.6.1 *General.*—The results of torsion tests on round tubes or round solid sections are sometimes plotted as torsion stress-strain diagrams. The modulus of elasticity in shear as determined from such a diagram is a basic shear property. Other properties, such as the proportional limit and ultimate shear stress, cannot be treated as basic properties because of the "form factor" effects.

1.4.6.2 *Modulus of Rigidity (G).*—This property is the ratio of the shear stress to the shear strain at low loads, or simply the initial slope of the stress-strain diagram for shear. It is also called the modulus of elasticity in shear. The relation between this property, Poisson's ratio, and the modulus of elasticity in tension is expressed for homogeneous isotropic materials by the following equation:

$$G = \frac{E}{2(1 + \mu)} \qquad [(1.4.6.2]$$

1.4.6.3 *Proportional Limit in Shear (F_{sp}).*—This property is of particular interest in connection with formulas, which are based on considerations of perfect elasticity, as it represents the limiting value of shear stress to which these formulas can be accurately applied. As previously noted, this property cannot be determined directly from torsion tests. The results of research at the National

Bureau of Standards show that the ratio of the proportional limit in shear to the proportional limit in tension can be assumed to be approximately 0.55 for the most materials.

1.4.6.4 *Yield and Ultimate Stress in Shear.*—These properties, as usually obtained from torsion tests, are not strictly basic properties, as they will depend on the shape of the test specimen. In such cases, they should be treated as moduli and should be used only with specimens, which are geometrically similar to those from which the test results were obtained.

The values for ultimate shear stress reported in the room-temperature property tables for the aluminum and magnesium sheet alloys are based on "punch" shear-type tests except as noted. Heavy section data are based on pin tests. The shear data on other alloys were also obtained from "pin" shear tests, except where thicknesses were too small.

1.4.7 BEARING PROPERTIES

1.4.7.1 *General.*—Bearing strengths are of value in the design of joints and lugs. Only yield and ultimate values are obtained from bearing tests. The bearing stress is obtained by dividing the load on a pin, which bears against the edge of a hole, by the bearing area, where the area is the product of the pin diameter and sheet thickness.

The bearing test requires the use of special cleaning procedures as specified in ASTM E 238. In the various room-temperature property tables in this document, when the indicated values are based on tests with clean pins, the values are footnoted as "dry pin values". See Reference 1.4.7.1 for additional information. Designers should consider the use of a reduction factor in applying these values to structural analyses.

In the definition of bearing values, t is sheet thickness, D is the hole diameter, and e is the edge distance measured from the hole center to the edge of the material in the direction of applied stress. Tabular values of static joint strengths are for e/D equal to 2. Bearing stress values for e/D of 1.5 shall not be used for e/D < 1.5. Bearing values for e/D < 1.5 shall be substantiated by adequate tests, subject to the approval of the procuring or certificating agency. For edge distance ratios between e/D equal to 2 and e/D equal to 1.5, linear interpolation may be used.

Bearing values are applicable to t/D ratios from 0.18 to 1.00. Bearing values for t/D < 0.18 or > 1.00 must be substantiated by test. The percentage curves showing temperature effects on bearing strength may be used with e/D values of 1.5 and 2.0.

1.4.7.2 *Yield and Ultimate Bearing Stresses.*—F_{bru} is the maximum stress withstood by a bearing specimen, and F_{bry} is the stress at an offset of 2 percent of the hole diameter of a bearing stress-deformation curve.

1.4.8 TEMPERATURE EFFECTS

1.4.8.1 *Low Temperature.*—Temperatures below room temperature generally cause an increase in all strength properties of metals. Ductility usually decreases. For specific information, see the applicable chapter and references noted therein.

1.4.8.2 *Elevated Temperature.*—Temperatures above room temperature usually cause a decrease in the strength properties of metals. This decrease is dependent on many factors, such as temperature and time of exposure and the characteristics of the material. Ductility may increase or decrease with increasing temperature depending on the same variables. Because of this dependence of strength and ductility at elevated temperatures on many variables, it is emphasized that the elevated-temperature properties given hereafter for specific materials apply only to the stated condition.

The effect of temperature on the static mechanical properties of various metals illustrated by means of a series of graphs of property (as percent of room temperature design allowable) versus temperature. The data for these graphs have been obtained from tests made over a limited range of strain rate. Some caution should be observed in using these static property curves at very high temperatures, particularly if the strain rate in the structure is much less than the strain rate used to

obtain the basic material properties. The reason for this is that at very low strain rates or under sustained stresses, plastic deformation or creep deformation may occur to the detriment of the intended structural use.

1.4.8.2.1 *Creep and Stress-Rupture Properties—*

General.—Creep is defined as the time-dependent deformation of a material under an applied load. It is usually regarded as an elevated-temperature phenomenon, although some materials creep at room temperature. If permitted to continue indefinitely, creep terminates in rupture. Since creep in service is usually typified by complex conditions of loading and temperature, the number of possible stress-temperature-time profiles is infinite. For economic reasons, creep data for general design use are usually obtained under conditions of constant uniaxial load and temperature. Creep data are sometimes obtained under conditions of cyclic uniaxial load and constant temperature (see Section 9.3.6). It is recognized that, when significant creep appears likely to occur, it may be necessary to test under actual service conditions because of difficulties in extrapolating from the simple to the complex stress-temperature-time conditions.

Damage incurred in a material as a result of creep (including effects resulting from elevated-temperature exposure) is cumulative. This damage may involve the tempering or annealing of hardened materials and the initiation and growth of cracks and voids (initially of microscopic size) within a material. Its effects are often recognizable as a reduction in short-time strength properties or ductility, both at room and at elevated temperatures.

Creep-Rupture Curve.—The results of tests of materials under a constant load and temperature are usually plotted as strain versus time up to a rupture. A typical plot of creep-rupture data is shown in Figure 1.4.8.2.1(a). The strain indicated in this curve includes both the instantaneous deformation due to loading and the plastic strain due to creep. Other definitions and terminology are included in Section 9.3.6.2.

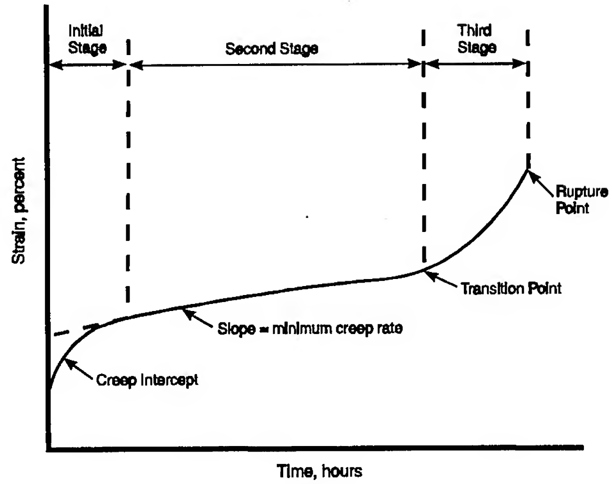

FIGURE 1.4.8.2.1(a). *Typical creep-rupture curve.*

Creep or Stress Rupture Data Presentations.—The results of creep or stress rupture tests conducted over a range of stresses and temperatures are presented as creep or stress rupture curves such as those presented in Figure 1.4.8.2.1(b). The data points represent time to X percent strain or stress rupture for specific stresses and temperatures. The curves represent a best-fit representation of the data trends using a Larson-Miller parameter or similar consolidation equation. Further details on the analysis methods are given in Section 9.3.6 and Reference 1.4.8.2.1(a).

Some creep data are still presented in creep nomographs as shown in Figures 5.4.1.2.7, 6.3.8.1.7, and 6.4.1.1.7. For these cases, the analysis and presentation were based primarily on Reference 1.4.8.2(b). The presentation of creep data in the form of a nomograph is not in compliance with Section 9.3.6. Therefore, these creep nomographs will be replaced in the near future.

1.4.9 FATIGUE PROPERTIES

1.4.9.1 *General.*—Repeated loads are one of the major causes for reducing design allowable stresses below those listed in the various tables of static properties (F_{tu}, F_{ty}, etc.). These reductions vary extensively in degree and are a function of the design practices of the producer of parts.

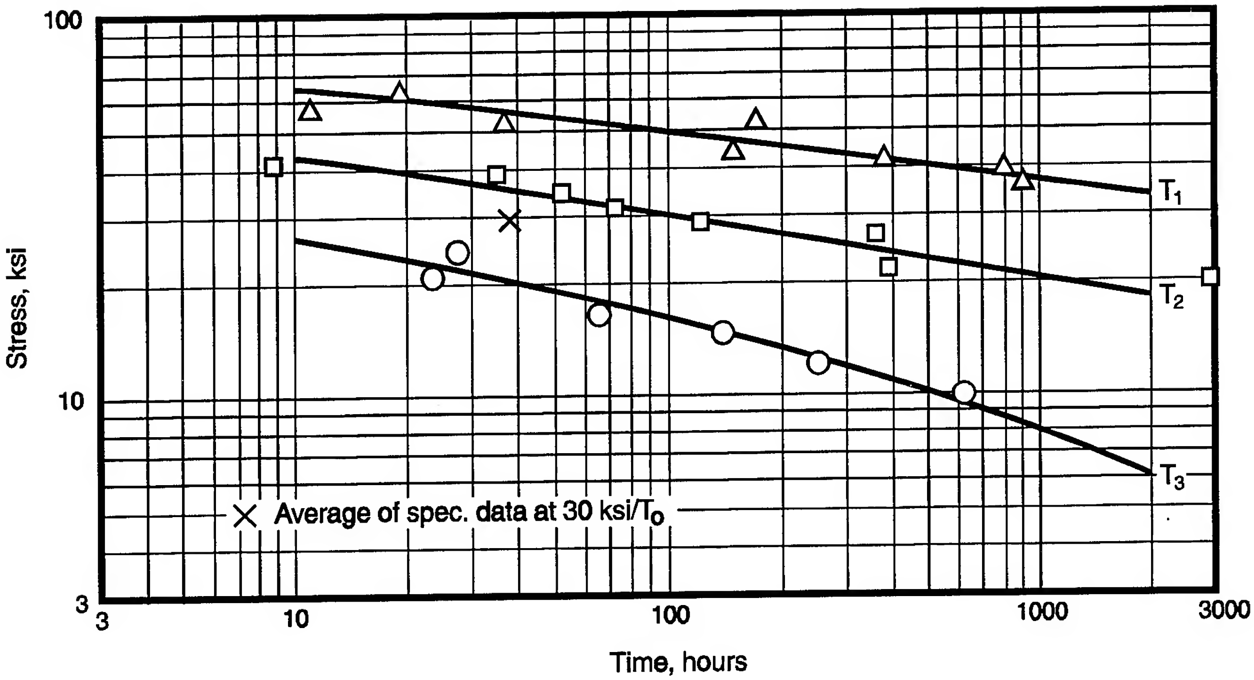

FIGURE 1.4.8.2.1(b). *Typical creep or stress-rupture curves.*

Therefore, no discussion of design use of fatigue (repeated load) data is included herein. However, some basic laboratory test data are useful in the materials selection and preliminary design processes and such data are therefore provided in the appropriate materials section, whenever available.

In the past, common methods of obtaining and reporting repeated load (fatigue) data included axial-loading tests, plate bending tests, rotating bending tests, and torsion tests. Rotating bending tests apply completely reversed (tension-compression) stressing to round specimens. Tests of this type are now seldom conducted for aerospace use and have therefore been dropped. For similar reasons, flexure fatigue data also have been dropped. No significant amount of torsional fatigue data have ever been available. Axial loading tests, the only type retained herein, not only can consist of completely reversed loading (mean stress equals zero), but the mean stress can be varied.

1.4.9.2 *Terminology.*—A number of symbols and definitions are commonly used in fatigue studies. The most important of these are presented in Section 9.3.4.2.

1.4.9.3 *Graphical Display of Fatigue Data.*—The results of axial-load and axial-strain fatigue tests are reported on S-N and ε-N diagrams, respectively. Figure 1.4.9.3(a) shows a family of axial load S-N curves for a material, the data for each curve having been taken at a single stress ratio, R.

S-N and ε-N diagrams are shown in MIL-HDBK-5 with the raw data plotted for each stress or strain ratio or, in some cases, mean stress. A best-fit curve is drawn through the data at each test condition. For load-control fatigue data, the individual curves are normally based on an equivalent stress consolidation of the data at all stress ratios, as shown in Figure 1.4.9.3(b). For strain-control fatigue data, an equivalent strain consolidation is used.

Elevated temperature fatigue data are treated in the same manner as room temperature data, as long as creep is not a major factor and room temperature analysis methods can be successfully applied. In the limited number of cases where creep-strain data have been recorded as a part of an elevated temperature fatigue test series, S-N (or ε-N) plots are constructed for specific creep-strain

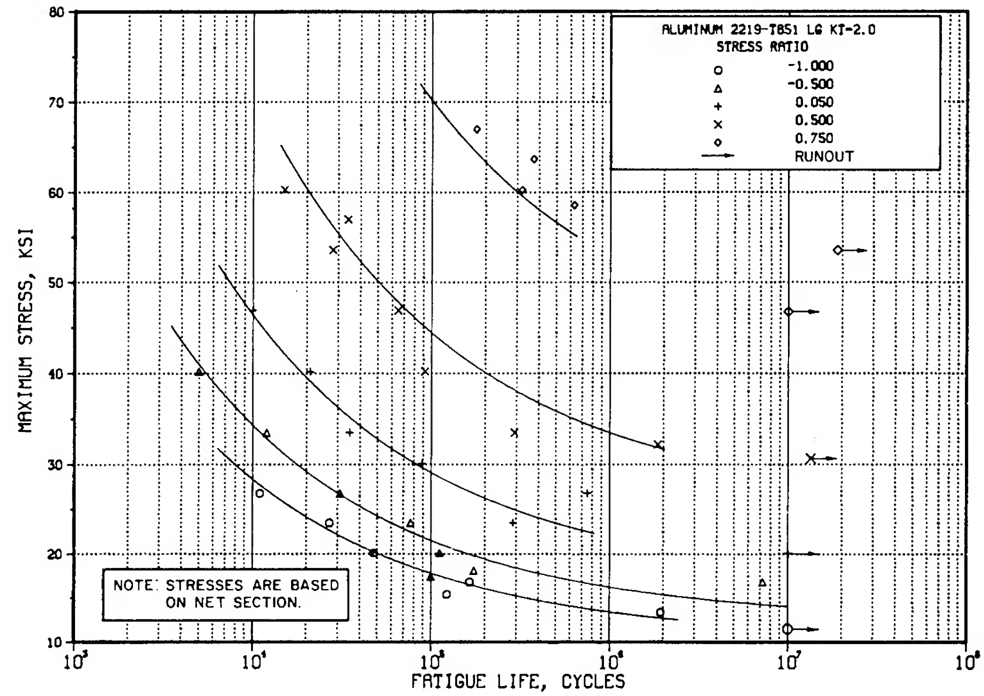

FIGURE 1.4.9.3(a). *Best fit S/N curve diagram for a material at various stress ratios.*

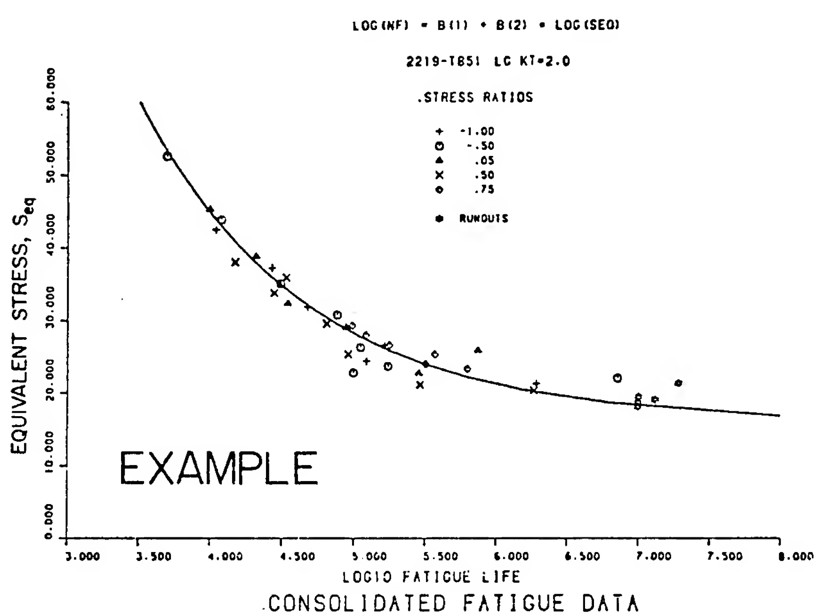

FIGURE 1.4.9.3(b). *Consolidated fatigue data for a material using the equivalent stress parameter.*

levels, in addition to the customary plot of maximum stress (or strain) versus cycles to failure.

The S-N or ε-N curves may not apply directly to the design of structures because they may not take into account the effect of specific stress concentration associated with reentrant corners, notches, holes, joints, rough surfaces, and other similar conditions, which are present in fabricated parts. The localized high stresses induced in fabricated parts by such stress raisers are of much greater importance for repeated loading than they are for static loading. They reduce the fatigue life of fabricated parts far below that which would be predicted by comparing the smooth-specimen fatigue strength directly with the nominal calculated stresses for the parts in question. Fabricated parts in test have been found to fail at less than 50,000 repetitions of load when the nominal stress was far below that which could be repeated many millions of times of a smooth machined specimen.

The notched fatigue data in the figures are presented so that by comparing the notched data with those from smooth specimens, the serious effect of a sharp notch on fatigue strength can be seen. All of the mean fatigue curves presented in MIL-HDBK-5, including both the notched fatigue and smooth specimen fatigue curves, should be reduced either by a factor in life or stress (strain where applicable) or both if they are going to be used in design. The specific reduction factor that is required depends on the criticality of the application, the sources of uncertainty in the analysis, and the requirements of the certifying body.

References 1.4.9.3(a) and (b) contain more specific information on fatigue testing procedures, organization of data, the influence of various factors on fatigue, and on design considerations.

1.4.10 METALLURGICAL INSTABILITY—In addition to the retention of load-carrying ability and ductility, a structural material must also retain surface and internal stability. Surface stability refers to the resistance of the material to oxidizing or corrosive environments. Lack of internal stability is generally manifested by carbide precipitation, spheroidization, sigma-phase formation, temper embrittlement, and internal or structural transformation, depending upon the material and conditions.

Environmental conditions, which may influence metallurgical stability include (a) heat, (b) stress, (c) oxidizing or corrosive media, and (d) nuclear radiation. The effect of the environment on the material may be indicated as either improvement or deterioration of properties, depending upon the way the material is evaluated. For example, prolonged heating may progressively raise the strength of a metal as measured on smooth tensile or fatigue specimens, but at the same time lower the ductility to such an extent that notched behavior is erratic or unpredictable. The metallurgy of each alloy should be considered in selecting any material listed herein.

Under normal temperature, i.e., between -65 F, and + 160 F, the stability of most structural materials is relatively independent of time. However, as the temperature increases the metallurgical stability of a material becomes increasingly time dependent and the factor of time assumes a more prominent role in material behavior and selection.

1.4.11 BIAXIAL PROPERTIES

1.4.11.1 *General.*—Discussions up to this point have been directed primarily to uniaxial conditions, whether the subject was static, fatigue, or creep loading. In actuality, many structural geometries, or load applications, are such that induced stresses are not uniaxial, but are bi- or triaxial. Because of the difficulty in testing, few triaxial stress data exist. However, considerable biaxial testing has been conducted and the following paragraphs describe how the results are presented in this Handbook. If stresses are referred to the mutually perpendicular x, y, and z directions of the usual rectangular coordinates, a biaxial stress is a condition such that there are either positive or negative stresses in the x and y directions and the stress in the z direction is essentially zero. Most of the discussion hereafter is concerned with x and y direction stresses, which are both tensile (see Reference 1.4.11.1).

When a specimen of a material is tested under biaxial loading conditions, it is customary to plot the results of such a test as a biaxial stress-strain diagram". These diagrams are similar to the tensile stress-strain diagrams shown in Figure 1.4.4.1. Usually, only the maximum (algebraically larger)

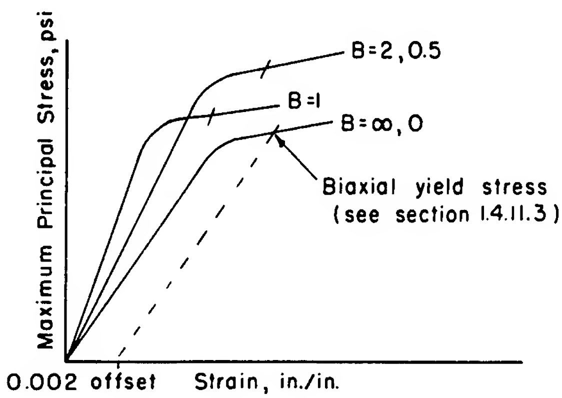

Figure 1.4.11.1 *Typical biaxial stress-strain diagrams for isotropic materials.*

principal stress and strain are shown for each test. When tests of the same material are conducted at various biaxial ratios, the resulting curves may be plotted simultaneously, producing a "family" of biaxial stress-strain curves as shown in Figure 1.4.11.1 for an isotropic material. For an anisotropic material, the curve for a given biaxial ratio would not coincide with the curve for the reciprocal of the biaxial ratio. The reference direction for biaxial ratio (i.e., direction corresponding to B = O) should clearly be indicated on the figure. The reference direction is the longitudinal (rolling) direction for flat products and the hoop (circumferential) direction for shells of revolution (tubes, cones, etc.).

The biaxial property data presented in the Handbook are to be considered a basic material properties obtained from tests on carefully prepared specimens. The stress values reported here may not be attainable in full scale structures, depending upon weld quality and other fabricational factors (see Reference 1.4.11.1 for further information).

1.4.11.2 *Biaxial Modulus of Elasticity.*— Referring to Figure 1.4.11.1, it will be noted that the first part of the diagram is substantially a straight line. In uniaxial tension, the slope of this line is defined as the "modulus of elasticity" (see Section 1.4.4.2). Under biaxial loading conditions this slope, now called the "biaxial modulus of elasticity", is affected by the biaxial ratio and Poisson's ratio (see Equation 1.3.7.4).

1.4.11.3 *Biaxial Yield Stress.*—Just as the tensile yield stress (F_{ty}) is defined arbitrarily as the uniaxial stress 0.002 inch/inch "offset" or permanent strain, as determined from the tensile stress strain curve, the biaxial yield stress is defined as the maximum principal stress at 0.002 inch/inch offset strain, as determined from the biaxial stress strain curve.

In design of aircraft and missile structures, biaxial ratios other than those normally used in biaxial testing are frequently encountered. For convenience in interpolating at intermediate biaxial ratios, biaxial yield-stress values are shown as biaxial yield-stress "envelopes", as illustrated in Figure 1.4.11.3. In preparing these envelopes,

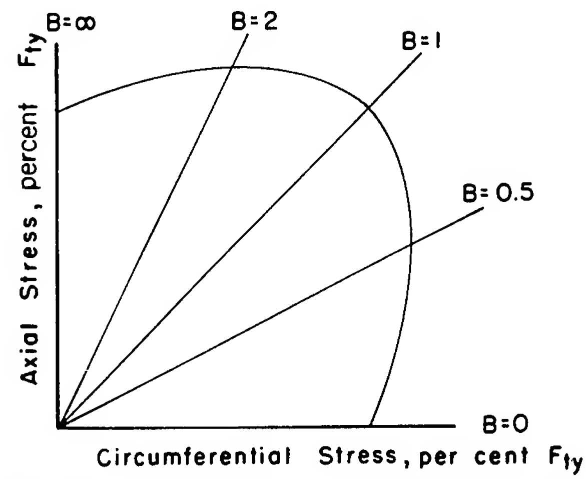

FIGURE 1.4.11.3. *Typical biaxial yield stress envelope.*

data are first reduced to nondimensional form (percent of uniaxial tensile yield stress in the specified reference direction), then a best curve is fitted to the reduced data. Biaxial yield-strength values, for design are then obtained by multiplying the F_{ty} for the specified material by the coordinates of the curve (in percent) at the appropriate biaxial ratio. To avoid possible confusion, the reference direction used for the uniaxial yield strength is indicated on each figure.

The local value of the biaxial ratio should be used in approving biaxial yield stress data to design. Thus, although a sheet may have a gross loading with a biaxial ratio of one, at each free (unloaded) edge or hole, the local stress system is uniaxial and the local biaxial ratio is either zero or infinity. A similar precaution applies to material in the vicinity of loaded holes (e.g., rivet holes,

bolt holes) and to discontinuities in cross section, such as those occurring as a result of integral stiffeners.

1.4.11.4 *Biaxial Ultimate Stress.*—Biaxial ultimate stress is defined as the highest nominal principal stress reached in specimens of a given configuration, tested at a given biaxial ratio. Unlike uniaxial ultimate tensile stress (F_{tu}), biaxial ultimate stress is often highly dependent upon the geometrical configuration. Thus, ultimate stress data obtained from tests on cylindrical vessels should be limited to cylindrical-vessel applications, flat-sheet data only to flat-sheet applications, etc.

The method of preventing biaxial ultimate-stress data is similar to that described in Section 1.4.11.3. Where nominal strains at biaxial ultimate stress values are available, they are reported as a function of biaxial ratio.

1.4.12 FRACTURE STRENGTH

1.4.12.1 *General.*—The occurrence of flaws in a structural component is an unavoidable circumstance of material processing, fabrication, or service. The flaws may be cracks, metallurgical inclusions or voids, weld defects, design discontinuities, or some combination thereof. If severe enough, these flaws can induce structural failure at loads below those of the nominal design. The fracture strength of a component containing a flaw is dependent on the flaw size, the component geometry, and a material property termed "fracture toughness".

The fracture toughness of a material is literally a measure of its resistance to fracture. It also is considered a measure of its tolerance or lack of sensitivity to flaws. As with many other material properties, fracture toughness is dependent on processing variables, product form, geometry, temperature loading rate, and other environmental factors. Many measures of fracture toughness have evolved. Those based on crack stress or strain analysis are more meaningful for use in design applications. Other measures are useful for qualitative evaluation of materials; however, they have proven to be difficult to apply to specific design configurations.

While there are several types of fracture, this discussion is limited to brittle fracture, which is characteristic of high-strength materials in structural configurations, which approach plane-strain conditions by nature of their bulk thickness or geometric constraint. Little plasticity accompanies the fracture. The following is based on the current practice of testing specimens of materials under slowly increasing loads. Attendant and interacting conditions of cyclic loading, prolonged static loadings, environmental influences other than temperature, and high-strain rate loading are not considered.

1.4.12.2 *Brittle Fracture.*—For materials, which have little capacity for plastic flow, or for flaw and structural configurations, which induce triaxial tension stress states adjacent to the flaw, component behavior is essentially elastic until the fracture stress is reached. Then, a crack propagates from the flaw suddenly and completely through the component. A convenient illustration of brittle fracture is a typical load compliance record of a brittle structural component containing a flaw, as illustrated in Figure 1.4.12.2. Since little or no plastic effects are noted, this mode is termed brittle fracture. This mode of fracture is

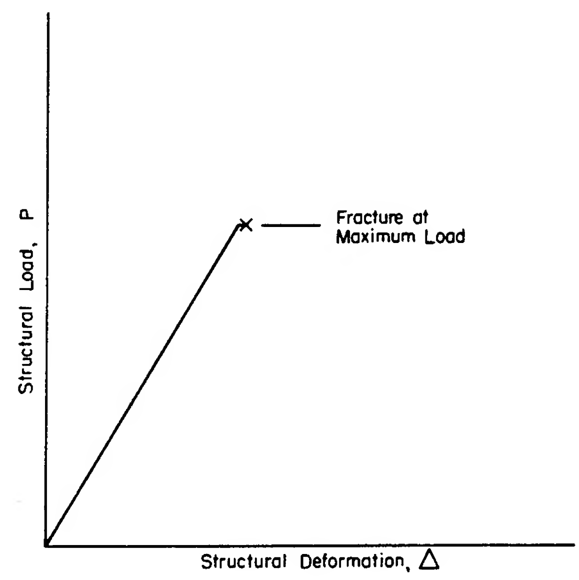

FIGURE 1.4.12.2. *Typical load-deformation record of a structural component containing a flaw subject to brittle fracture.*

somewhat characteristic of the very high-strength metallic materials under plane strain conditions.

1.4.12.2.1 *Brittle Fracture Analysis.*—The application of linear elastic fracture mechanics has led to the stress intensity concept to relate flaw size, component geometry, and fracture toughness. In a very general form, the stress intensity factor, K, can be expressed as

$$K = f\sqrt{a}\ Y,\ \text{ksi-in.}^{1/2} \qquad [1.4.12.2.1]$$

where

f = stress applied to the gross, flawed section, ksi

a = measure of flaw size, inches

Y = factor relating component geometry and flaw size, nondimensional. See Reference 1.4.12.2.1(a) for values.

For every structural material, which exhibits brittle fractures (by nature of low ductility or plane-strain stress conditions), there is a lower limiting value of K termed the plane-strain fracture toughness, K_{Ic}.

The specific application of this relationship is dependent on flaw type, structural configuration and type of loading, and a variety of these parameters can interact in a real structure. Flaws may occur through the thickness, may be imbedded as voids or metallurgical inclusions, or may be partial-through (surface) cracks. Loadings of concern may be tension and/or flexure. Structural components may vary in section size and may be reinforced in some manner. The ASTM Committee E-24 on Fracture Testing of Metals has developed testing and analytical techniques for many practical situations of flaw occurrence subject to brittle fracture. They are summarized in References 1.4.12.2.1(a), (b), and (c).

1.4.12.3 *Critical Plane-Strain Fracture Toughness Values.*—In the general discussion prefacing each alloy chapter, a tabulation of fracture toughness values is printed. These critical plane-strain fracture toughness values, K_{Ic}, have been determined by the recommended ASTM testing practice. Since the data on a given alloy and product form are generally limited, these data are for information only and do not have the statistical reliability normally associated with the room temperature mechanical properties. In general, these data are available only for the high strength alloys in relatively thick sections.

The directional significance of the fracture toughness value relative to the grain direction of the material may be identified by an ordered pair of grain direction symbols. The first digit of the pair denotes the grain direction normal to the crack plane; the second digit of the pair denoted the grain direction parallel to the fracture direction. Thus, the six principal fracture path directions may be denoted as:

L-T	T-S
L-S	S-L
T-L	S-T .

Figure 1.4.12.3 illustrates the six principal fracture path directions.

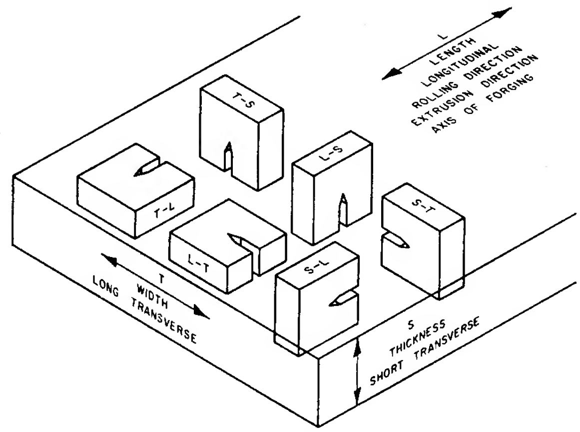

FIGURE 1.4.12.3. *Typical principal fracture path directions.*

1.4.12.3.1 *Environmental Effects.*—As noted in 1.4.12.1, all fracture-toughness data presented in this document represent data obtained under single application of a steadily increasing load in air. Cyclic loading, even well below the fracture threshold stress, may result in propagation of flaws, leading to fracture. Strain rates in excess of those normally used in testing may cause variations in material behavior. There are distinct effects of temperature on fracture toughness properties.

A very limited quantity of effect of temperature data is available for fracture toughness properties. Where these are available, they are incorporated in each alloy section.

It has been noted that under sustained loads some materials exhibit increased flaw-propagation tendencies in aqueous or corrosive environments. When such is known to be the case, appropriate precautionary notes have been included in the alloy chapters.

1.4.12.4 *Fracture in Plane Stress and Transitional Stress States.*—In many structural components, plane strain conditions are never manifested because of the thinness of the product form and the intrinsic ductility of the material. In these cases, the actual stress state may approach the opposite extreme, plane stress, or, more generally, some intermediate or transitional stress state. Flaws or cracks, which may occur in these stress states behave differently than those in plane strain. Under loading, due to lesser crack tip constraint, significant plastic zones may develop adjacent to the crack tip, and stable extension of the crack may occur by a slow tearing process. This more complex behavior is exhibited in the compliance record as a significant nonlinearity prior to fracture such as shown in Figure 1.4.12.4. This nonlinearity results from the lessening stiffness, which accompanies plastic-zone development and from the reduced cross-sectional area resulting from crack extension.

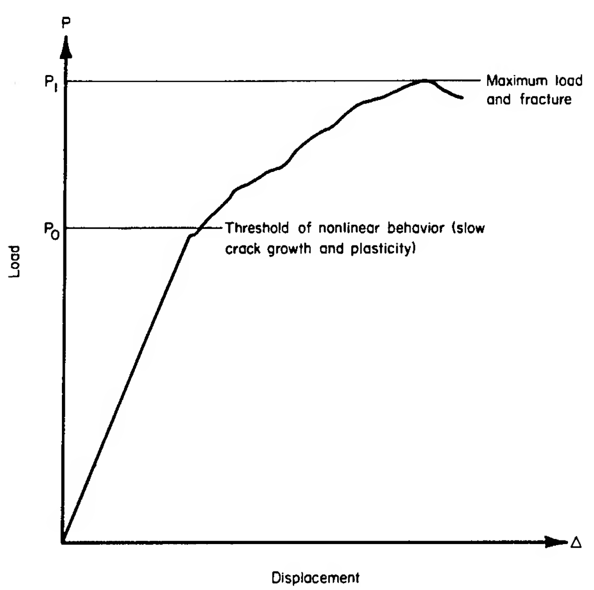

FIGURE 1.4.12.4 *Typical load-deformation record for nonplane strain fracture.*

1.4.12.4.1 *Analysis of Plane Stress and Transitional Stress State Fracture.*—Although the physical problem is much more complex, the basic concepts of linear elastic fracture mechanics as used in plane strain fracture analysis may be applied here also. The stress intensity factor concept, as expressed in general form by Equation 1.4.12.2.1, is used to relate load or stress, flaw size, component geometry, and fracture toughness. However, the interpretation and assignation of critical stress intensity factors must be accomplished with much greater care. In Figure 1.4.12.4, it can be seen that there are at least two and possibly more points on the load-deformation curve to which it would be important to assign K values. These are the point of onset of nonlinearity and the point of fracture, each of which generally will occur at different stress levels, as well as different crack lengths due to stable tear.

This becomes clearer when the compliance record is transformed into the crack growth curve on the stress-flaw size coordinate system format illustrated in Figure 1.4.12.4.1. In most practical cases, however, the definition and precise experimental discrimination of the point of onset of nonlinearity and the point of fracture are very elusive.

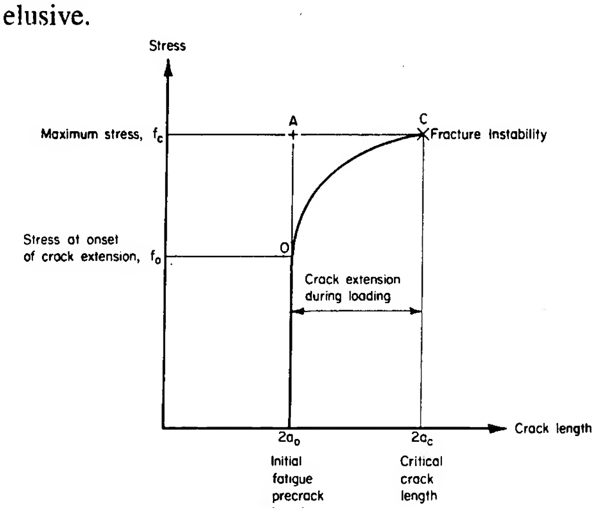

FIGURE 1.4.12.4.1 *Crack growth curve.*

As a result, an alternate characterization of the fracture behavior can be achieved by calculating an artificial or "apparent" stress intensity factor,

$$K_{app} = f\sqrt{a_0}\; Y \qquad [1.4.12.4.1]$$

using the maximum stress and the initial flaw size. This datum coordinate corresponds to the Point A

in Figure 1.4.12.4.1 and its associated stress-intensity factor K_{app}, is a first approximation to the actual K values which may be associated with either the onset of nonlinearity or the point of fracture.

1.4.12.5 *Apparent Fracture Toughness Values for Plane Stress and Transitional Stress States.*— In each alloy chapter, basic fracture data are presented on a graphical format of stress versus flaw size for each alloy, temper, product form, grain direction, thickness, and specimen configuration where data are available. The data points shown represent the initial flaw size and maximum stress for that test point. The data presented have been screened to assure that there was a bona fide elastic instability at fracture consistent with the specimen type. The average K_{app} curve, as defined in the following subsections, is shown for each set of data.

1.4.12.5.1 *Center-Cracked Tension Panels.* — The formulation of the apparent fracture toughness for center-cracked tension panels is

$$K_{app} = f_c(\pi a_0 \sec \Pi a_0/W)^{1/2} \qquad [1.4.12.5.1(a)]$$

The data points used to determine the K_{app} values have been screened to assure that the net section stress at failure did not exceed 80% of the tensile yield strength; that is, they satisfied the criterion

$$f_c \leq 0.8\ (TYS)/(1\text{-}2a/W) \qquad [1.4.12.5.1(b)]$$

This criterion assures that the fracture was an elastic instability and that plastic effects are negligible.

The average K_{app} parametric curve is presented on each figure as a solid line with multiple extensions where width effects are displayed in the data. As additional information, where data are available, the propensity for slow stable tear prior to fracture is indicated by a crack extension ratio, $2a/2a_0$. In some cases, where data exist covering a wide range of thickness, graphs of K_{app} versus thickness are presented.

1.4.13 FATIGUE-CRACK-PROPAGATION BEHAVIOR

1.4.13.1 *General.*—Between the crack initiating phenomenon of fatigue and the critical instability of cracked structural elements as identified by fracture toughness and residual strength lies an important facet of material behavior known as fatigue-crack propagation. In small-size laboratory fatigue specimens, crack initiation and specimen failure may be nearly synonymous. However, in larger structural components, the existence of a crack does not necessarily imply imminent failure of the component. Significant structural life is accountable in the cyclic crack extension (subcritical crack growth) which can be tolerated prior to reaching conditions critical for fracture.

1.4.13.2 *Fatigue-Crack Growth.*—The physical or mechanical phenomenon of fatigue-crack propagation is manifested as the growth or extension of a crack under cyclic loading. While this process is principally controlled by maximum load and stress ratio, there are a number of additional factors, such as environment, frequency, temperature, and grain direction, which may exert a strong influence, depending on the material sensitivities. While it is important to alert the Handbook user to the complexity of this mode of crack behavior, only certain basic principles can be considered here. In particular, it should be noted that in addition to stress ratio effects, the next important consideration is the potentially synergistic interaction of environment and frequency. When environment is important, it is usually important from the perspective of corrosion processes. Thus, time-at-stress as controlled by frequency also becomes an important factor.

The basic experimental data characterizing fatigue-crack growth that are shown in this Handbook are based on constant amplitude crack-growth experiments. It should be acknowledged that data trends based on constant amplitude cycling may be different than those generated by spectrum cycling. The constant-amplitude data presented consist of crack-length measurements and the associated counts of loading cycles accumulated. Such data may be displayed in a crack-growth curve as illustrated in Figure 1.4.13.2(a).

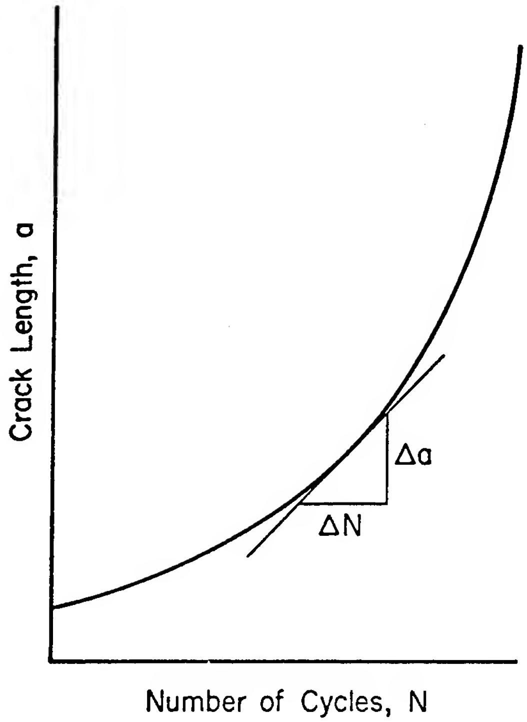

FIGURE 1.4.13.2(a) *Crack-growth curve.*

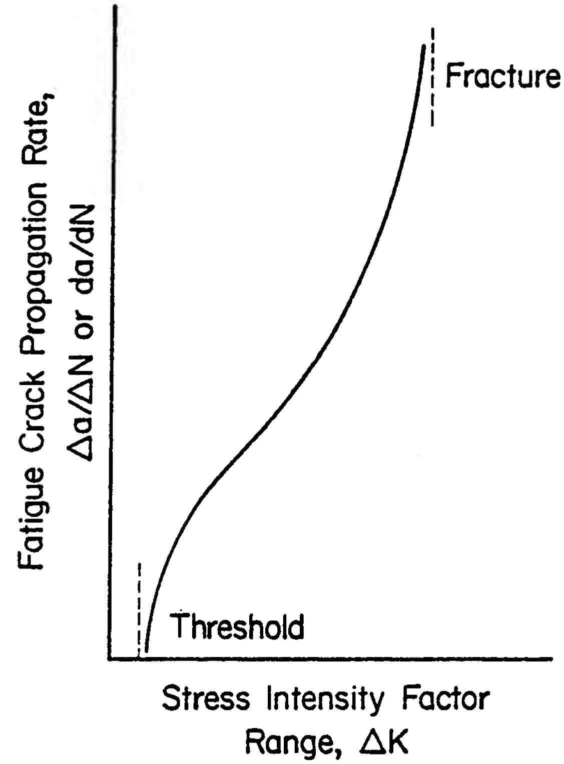

FIGURE 1.4.13.2(b). *Crack-growth-rate curve.*

However, since the crack-growth curve is dependent on initial crack length and the loading conditions, the presentation of crack-growth curves is not the most concise means of representing crack behavior in a material. As with many dynamic processes, the rate behavior or slope, $\Delta a/\Delta N$, of the crack-growth curve provides a more fundamental characterization of the behavior. In general, fatigue-crack-propagation rate behavior is evaluated as a function of the applied stress-intensity-factor range, as illustrated in Figure 1.4.13.2(b).

1.4.13.3 *Fatigue-Crack-Propagation Analysis.*—It is known that fatigue-crack-propagation behavior under constant-amplitude cyclic conditions is influenced by maximum cyclic stress, S_{max}, and some measure of cyclic stress range, ΔS (such as stress ratio, R, or minimum cyclic stress, S_{min}), the instantaneous crack size, a, and other factors such as environment, frequency, and temperature. Thus, fatigue-crack-propagation rate behavior can be characterized, in general form, by the relation

$$da/dN \approx \Delta a/\Delta N = g(S_{max}, \Delta S \text{ or } R \text{ or } S_{min}, a, ...). \quad [1.4.13.3(a)]$$

By applying concepts of linear elastic fracture mechanics, the stress and crack size parameters can be combined into the stress-intensity factor parameter, K, such that Equation 1.4.13.3(a) may be simplified to

$$da/dN \approx \Delta a/\Delta N = g(K_{max}, \Delta K, ...) \quad [1.4.13.3(b)]$$

where

K_{max} = the maximum cyclic stress-intensity factor

ΔK = $(1\text{-}R)K_{max}$, the range of the cyclic stress-intensity factor.

At present, in the Handbook, the independent variable is considered to be simply ΔK and the data are considered to be parametric on the stress ratio, R, such that Equation 1.4.13.3(b) becomes

$$da/dN \approx \Delta a/\Delta N = g(\Delta K, R). \quad [1.4.13.3(c)]$$

1.4.13.4 *Fatigue-Crack-Propagation Data Presentation.*—Fatigue-crack-propagation rate data for constant-amplitude cycling conditions are presented on a doubly logarithmic graphical format of

rate, da/dN, versus applied stress-intensity-factor range, ΔK. The figures, illustrated in Figure 1.4.13.4, are ordered by material, alloy, and heat treatment, in the respective alloy chapters. Parametric variations of rate behavior presented as graphical data with stress ratio, R, environment, and frequency are displayed where data are available. Background information, test procedures, and interpretative discussion of this type of crack behavior are presented in Chapter 9.

1.5 Types of Failures

1.5.1 GENERAL.—In the following discussion, "failure" will usually denote actual fracture of the member, or the condition of the member when it has just attained its maximum load.

1.5.2 MATERIAL FAILURES

1.5.2.1 *General.*—Fracture of a metal can be very complex and will not be discussed thoroughly herein. Many references can be consulted for such information. It should be noted, however, that fracture can occur in either a ductile or brittle fashion, in the same material, depending on the state of stress and the environment. Additionally, metals are being used, which have higher strength and have resulted in lower ductility prior to fracture. Fracture can occur after elongation of the metal over a relatively large uniform length, or after a concentrated elongation in a short length. Shear deformation will also vary depending on metal and stress state. Because of these variations in magnitude and mode of deformation, the ductility of a metal can have a profound effect on the ability of a fabricated part to withstand applied loads. Although not a specific design property, some ductility data are provided for each metal to assist in materials selections. Following paragraphs discuss the relation of failure to applied or induced stresses.

1.5.2.2 *Direct Tension or Compression.*—This type of failure is associated with ultimate tensile or compressive stress of the material. For compression, it can apply only to members having large cross-sectional dimension as compared to the length in the direction of the load (see 1.4.5.2).

1.5.2.3 *Shear.*—Pure shear failures are usually obtained only when shear load is transmitted over a very short length of the member. This condition is approached in the case of rivets and bolts. In cases where ultimate shear stress is relatively low, a pure shear failure may result, but in general a member subjected to a shear load fails under the action of the resulting normal stress (Equation 1.3.3.3), usually the compressive stress. The failure of a tube in torsion, for instance, is not usually caused by exceeding the allowable shear stress, but by exceeding a certain allowable normal compressive stress, which causes the tube to buckle. It is customary, for convenience, to determine the allowable stresses for members subjected to shear in the form of shear stresses. Such allowable shear stresses are therefore an indirect measure of the stresses actually causing failure.

1.5.2.4 *Bearing.*—The failure of a material in bearing may consist of crushing, splitting, or progressive rapid yielding in the region where the load is applied. Failure of this type will depend, to a large extent, on the relative size and shape of the two connecting parts. The allowable bearing stress will not always be applicable to cases in which one of the contacting members is relatively thin. It is also necessary, for practical reasons, to limit the working bearing stress to low values in such cases as joints subjected to reversals of load or in bearings between removable surfaces. These special cases are covered by specific rulings of the procuring or certificating agency, involving the use of higher factors of safety in most cases.

1.5.2.5 *Bending.*—For compact sections not subject to instability, a bending failure can be classed as a tensile or compressive failure caused by exceeding a certain allowable stress in some portion of the specimen. It is customary to determine, experimentally, the "modulus of rupture in bending", which is a stress derived from test results through the use of Equation 1.3.2.3, in which Case M is the value of bending moment which caused failure. For compact sections not subject to instability, the treatment of bending in the plastic range by linear analog methods, for example, Cozzone (Reference 1.5.2.5), provides a method by which actual bending stresses above the material proportional limit can be related to the "bending modulus of rupture". From simple bending theory, the bending modulus of rupture is determined by Equation 1.3.2.3. When the modulus of rupture is less than or equal to the proportional limit, it

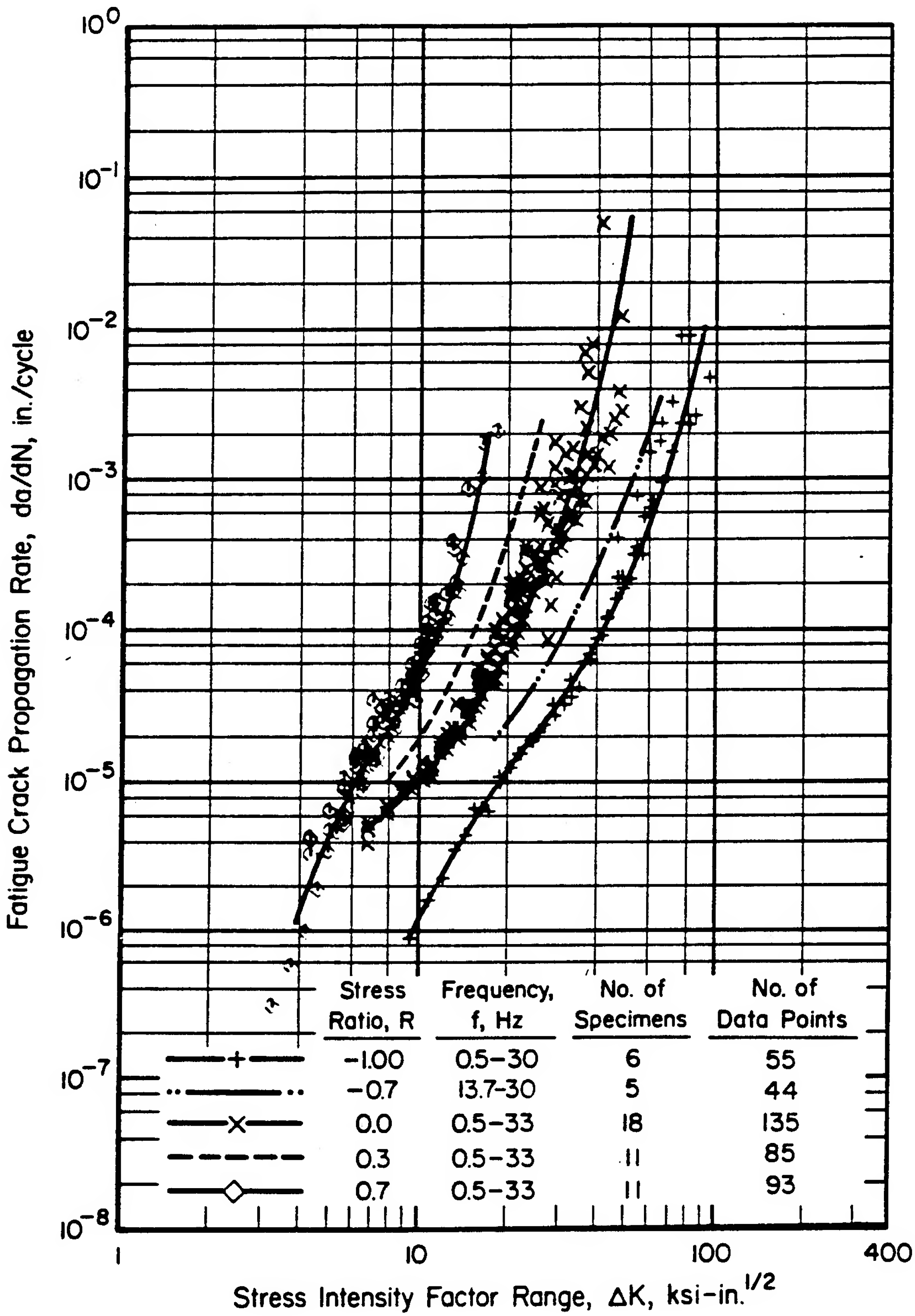

FIGURE 1.4.13.4. *Sample display of fatigue crack propagation rate data.*

represents an actual stress. When the modulus of rupture is greater than the proportional limit, it represents an apparent stress, which cannot be considered as the actual stress at the point of rupture. This should be borne in mind in dealing with combined stresses such as bending and compression or bending and torsion.

1.5.2.6 *Failure Due to Stress Concentration.*—The static strength properties listed for various materials were determined on machined specimens containing no notches, holes, or other avoidable stress raisers. In the design of aircraft structures, such simplicity is unattainable, and stress distributions are not of the uniform type obtained in the specimen tests. Consideration must be given to the effect of stress raisers since maximum stress in a material and not average stress, is the critical factor in design. The effects of stress raisers vary, and references to available specific data are given in the sections pertaining to each material.

1.5.2.6.1 *Failure, Due to Unintentional Flaws.*—As stated in 1.4.12.1, unintentional flaws may be metallurgical defects, such as inclusions, voids, seams, weld defects; they also may be surface defects from service, such as corrosion pits, stress-corrosion cracks, and fatigue cracks. Some high-strength materials are extremely sensitive to such small cracks or flaws, and their use has resulted in structural failure. In this context, the word "sensitive" means that for certain of the high-strength materials that inadvertently contain flaws, failure of the material or a part fabricated from it may occur at gross stress levels substantially below the yield strength. Universal agreement on a design accounting for this type of failure is still evolving. Plain-strain fracture toughness data are included in certain material chapters. Since for these high-strength materials premature fracture may occur, the possibility should be considered in design.

1.5.2.7 *Failure Resulting From Fatigue.*—Aircraft structures are subjected to repeated loads. It is well known that the strength of a material under such repeated loads is less than it would be under static loading. This phenomenon of the decreased strength of a material under repeated loading is commonly called fatigue. Stress raisers, such as abrupt changes in cross section, holes, notches, and reentrant corners, have a much greater effect on the fatigue strength than on static strength. The local high stress concentrations caused by such stress raisers are often greatly in excess of the nominal calculated stress on the part, and consequently it is at such locations that fatigue fractures usually begin. Other factors of major importance in fatigue are the range of the repeated stress cycle (from maximum to minimum stress), and the mean stress in the stress cycle. In the following chapters of this document, fatigue data are presented for various materials from axial load fatigue tests. The data are average or typical data and are not to be used as allowable stress values unless their applicability to the case at hand has been established.

1.5.2.8 *Failure From Combined Stresses.*—In combined-stress conditions where failure is not due to buckling or instability, it is necessary to refer to some theory of failure. The "maximum shear" theory has received wide acceptance as a simple working basis in the case of isotropic ductile materials. It should be noted that this theory interprets failure as the first yielding of the materials, so that any extension of the theory to cover conditions of final rupture must be based on the experience of the designer. The failure of brittle materials under combined stresses can generally be treated by the "maximum stress" theory. Section 1.4.11 has a more complete discussion of biaxial behavior. References 1.5.2.8(a) through (c) may also be helpful.

1.5.3 INSTABILITY FAILURES

1.5.3.1 *General.*—Practically all structural members such as beams and columns, particularly those made from thin material, are subject to failure through instability. In general, instability can be classed as: (1) primary or (2) local. For example, the failure of a tube under compression may occur either through lateral deflection of the tube as a column (primary instability) or by collapse of the tube wall at a stress lower than that required to produce a general column failure. Similarly, an I-beam or other shape may fail by a general sidewise deflection of the compression flange, by local wrinkling of thin outstanding flanges, or by torsional instability. It is obviously necessary to consider all types of failure, unless it is apparent that the critical load for one type is definitely less than that for the other type.

Instability failures may occur in either the elastic range (below the proportional limit) or in the plastic range (above the proportional limit). To distinguish between these two types of action, it is not uncommon to refer to them as "elastic instability failures" and "plastic instability failures", respectively. It is important to note that instability failures are not usually associated with the ultimate stresses of the material. This should be borne in mind when correcting test results for material variations. This point also has a bearing on the choice of a material for a given type of construction, as the "strength-weight ratio" will be determined from different physical characteristics when this type of failure can be expected.

A method of determining the local stability of aluminum alloy column sections is outlined in Reference 1.7.1(b). The documents cited in Reference 1.7.1(b) are the same as those listed in Chapter 3, References 3.20.2.2 (a) through (e).

1.5.3.2 *Instability Failures Under Compressive Loading.*—Failures of this type are discussed in Section 1.6 (Columns).

1.5.3.3 *Bending Instability Failures.*—Failures of round tubes of usual size when subjected to bending are usually of the plastic-instability type. In such cases, the criterion of strength is the modulus of rupture (Equation 1.3.2.3) which was derived from theory and checked by test. Elastic-instability failures of thin-walled tubes having high D/t ratios are treated in later sections.

1.5.3.4 *Torsional Instability Failures.*—The remarks of the preceding section apply in a similar manner to round tubes under torsional loading. In such cases, the modulus of rupture in torsion is derived through the use of Equation 1.3.2.6. See Reference 1.5.3.4.

1.5.3.5 *Failure Under Combined Loadings.*—For combined-loading conditions in which failure is caused by buckling or instability, no general theory exists, which will apply in all cases. Due to the various design philosophies and analytical techniques used throughout the aerospace industry, methods for computing margin of safety are not within the scope of MIL-HDBK-5.

1.6 Columns

1.6.1 GENERAL.— A theoretical treatment of columns can be found in standard textbooks on the strength of materials. The problems confronting the designer, however, include many points, which are not well defined by theory and which frequently cause some confusion. These are discussed in this section. Actual strengths of columns of various types are given in subsequent chapters.

1.6.2 PRIMARY INSTABILITY FAILURES

1.6.2.1 *General.*—A column may fail through primary instability by bending laterally (stable sections) or by twisting about some axis parallel to its own axis. This latter type of primary failure is particularly common to columns having unsymmetrical open sections. The twisting failure of a closed-section column is precluded by its inherently high torsional rigidity. Since the information available on twisting instability is somewhat limited, it may be advisable to conduct tests on all columns subject to this type of failure.

1.6.2.2 *Columns with Stable Sections.*—The tangent modulus formula for columns which fail by lateral bending is given by Equation 1.3.8. No explanation of this formula need be offered, as its derivation can be found in many standard textbooks on the strength of materials. The value to be used for the restraint coefficient, c, depends upon the degree of end fixity.

The true significance of the restraint coefficient is best understood by considering the end restraint as modifying the effective column length, as indicated by Equation 1.3.8. For a pin-ended column having zero end restraint, $c = 1.0$ and $L' = L$. A fixity coefficient or 2 corresponds to a reduction of the effective length to $1/\sqrt{2}$ or 0.707 times the total length.

The tangent modulus Equation 1.3.8 takes into account the plasticity of the material and is valid if the following conditions are met:

(a) The column adjusts itself to forcible shortening only by bending and not by twisting.

(b) No buckling of any portion of the cross section has occurred.

(c) Load is concentric with the longitudinal axis of the unloaded column.

(d) The cross section of the column does not vary along the column length.

The value of the compressive tangent modulus E_t at any given compressive stress F_c, can be determined from stress strain curves for the material. Figure 1.6.2.2 illustrates the use of this equation. For example, assume an L'/ρ of 22.2, and computing $\pi^2/(L'/\rho)^2$ gives a value of 0.02, which also equals F_c/E_t. Plot the line $F_c/E_t = 0.02$ on the tangent modulus curve. The point of intersection gives a value of 60 ksi for F_c and 3 x 10^6 psi for E_t.

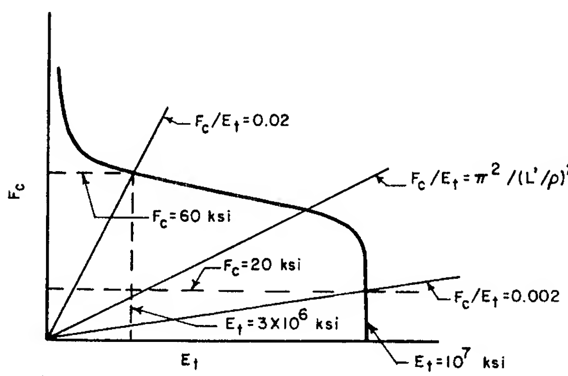

FIGURE 1.6.2.2 *Relation of $\pi^2/(L'/\rho)^2$ to tangent modulus.*

1.6.2.3 *Column Yield Stress (F_{co}).*—The upper limit of the allowable column stress for primary failure, designated F_{co}, may be obtained when not available elsewhere, from the compressive tangent modulus Equation 1.3.8 for columns including those having geometrical proportions for low values of L'/ρ, with the restriction that F_{co} shall not exceed F_{cu}, the material ultimate compressive stress. As discussed in 1.4.5.2, it is common practice to assume for wrought metals that the material ultimate compressive stress F_{cu}, is equal to the ultimate tensile stress.

1.6.2.4 *Other Considerations.*— Methods of analysis are available by which column failing stresses can be computed taking into account various fixities, torsional instability, load eccentricity, combined lateral loads, or varying column sections. References 1.6.2.4(a), (b), (c), and (d) present such methods.

1.6.3 LOCAL INSTABILITY FAILURE

1.6.3.1 *General.*— Columns may fail by a local collapse of the wall at a stress below the primary failure stress. The buckling analysis of a column subject to local instability requires taking into account the shape of the column cross section and may be quite complex. Local buckling, which may combine with primary buckling, leads to an instability failure commonly termed crippling.

1.6.3.2 *Crushing or Crippling Stress (F_{cc}).* — The upper limit of the allowable column stress for local failure is called the crushing or crippling stress and is designated F_{cc}. The crushing or crippling stresses of round tubes have been investigated frequently and considerable useful data exist. Fewer data are available for stresses of columns having other section configurations, and testing may be required to establish the curve of transition from local to primary failure.

1.6.4 CORRECTION OF COLUMN TEST RESULTS

1.6.4.1 *General.*—In the case of columns having unconventional cross sections, which are particularly subject to local instability, it is necessary to establish the curve of transition from local to primary failure. In determining the strength curves for such columns, sufficient tests should be made to cover the following points.

1.6.4.2 *Nature of "Short-Column Curve".*— The test specimens should cover a range of L'/ρ, which will extend to the Euler range, or at least well beyond the values to be used in construction. When columns are to be attached eccentrically in the structure, some tests should be made to determine the effects of eccentricity. This is important particularly in the case of open sections, as the allowable loads may be affected considerably by the location of the point of application of the column load.

1.6.4.3 *Local Failure.*—When local failure occurs, the crushing or crippling stress F_{cc}, can be determined by extending the "short-column" curve for the specific cross section under consideration to a point corresponding to zero L'/ρ. When a family of columns of the same general cross section is used, it is often possible to determine a relationship between F_{cc} and some factor depending on the wall thickness, width, diameter, or some combination of these dimensions. Extrapolations of such data should be avoided by covering an adequate range in the tests.

1.6.4.4 *Reduction of Column Test Results on Aluminum and Magnesium Alloys to Standard Material.*—The use of the correction factors given in Figures 1.6.4.4(a) through (i) is considered satisfactory and is acceptable in the Air Force, Navy, Army, and the Federal Aviation Administration for use in connection with tests on aluminum and magnesium alloys. (Note that an alternate method is given in Section 1.6.4.5). In using Figures 1.6.4.4(a) through (i), the correction of column test results to standard material is made by multiplying the stress obtained from testing a column specimen by the factor K. This factor may be considered applicable regardless of the type of failure involved (i.e., column crushing or crippling or twisting). In Figures 1.6.4.4(a) through (i), F_c' is the maximum test column stress of the test column material, and F_{cy} is the compressive yield stress as given in the design allowable property tables for the individual alloys.

Acceptable methods for obtaining compressive yield strength, F_{cy}', of column material for use in determining values of K from Figures 1.6.4.4(a) through (i) are as follows:

(a) Using a compression test specimen, obtain the compressive yield strength of the material from which the test column is made in the direction of loading of the test column.

(b) If Method (a) is not feasible, the compressive yield strength of column material may be obtained from the tensile yield strength as follows: Determine the tensile yield strength of the column material by conducting a standard tensile test in a direction parallel to the test-column length. Compute the compressive yield strength of the test column material by multiplying the tensile yield strength by the proper ratio of the design allowable compressive yield strength to the design allowable tensile yield strength. The ratio used should be compatible with the grain direction of the test column material. If the compression test column is manufactured indiscriminately with respect to material grain direction, the tensile test specimen should be oriented parallel to column length and the $F_{cy}(L)/F_{ty}(L)$ ratio for the material should be used.

(c) If neither Method (a) nor (b) is feasible, it can be assumed that compressive yield strength of column test specimen parallel to length is 15 percent greater than minimum established design allowable longitudinal tensile yield strength for material in the column test specimen.

1.6.4.5 *Reduction of Column Test Results to Standard Material-Alternate Method.*—For materials that are not covered by Figures 1.6.4.4(a) through (i), the following method should be used to reduce column test results to standard material. This method is acceptable to the Air Force, Navy, Army, and the Federal Aviation Administration.

(1) Determine the standard material compression allowables: F_{cy}, E_c, and n_c.

(2) Determine the test material critical column stress, f_c', and compression yield strength, f_{cy}'.

(3) Assume E_c and n_c of (1) apply to (2).

(4) Assume that the standard material and the column test material have the same critical slenderness ratio of (l'/ρ).

From (4), using the basic column formula from 1.3.8:

$$F_c/E_t(\text{std. mat'l.}) = f_c'/E_t(\text{test mat'l.}) \qquad (1)$$

where

$$E_t = F_c/[F_c/E_c + n_c(0.002)(F_c/F_{cy})^{n_c}] \qquad (2)$$

and

$$E_t' = f_c'/\left[f_c'/E_c + n_c(0.002)\left(f_c'/f_{cy}'\right)^{n_c}\right] \quad (3)$$

By substitution of Equations (2) and (3) into (1), simplification gives:

$$F_c/E_c + n_c(0.002)\left(F_c/F_{cy}\right)^{n_c} = f_c'/E_c + n_c(0.002)\left(f_c'/f_{cy}'\right)^{n_c} \quad (4)$$

The only unknown in (4) is F_c, which is the test material critical column compression allowable. It is determined by iteration.

This method is applicable at elevated temperatures, provided Young's modulus of the standard and test materials are equal. If modulus and shape factor of the test material are not the same as those of the standard material, the assumption stated in (3) is not valid. Equation (4) must account for these differences.

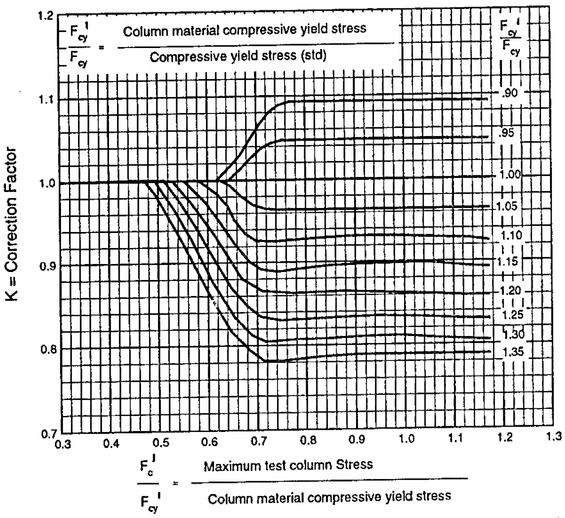

FIGURE 1.6.4.4(a). *Nondimensional material correction chart for 2024-T3 sheet.*

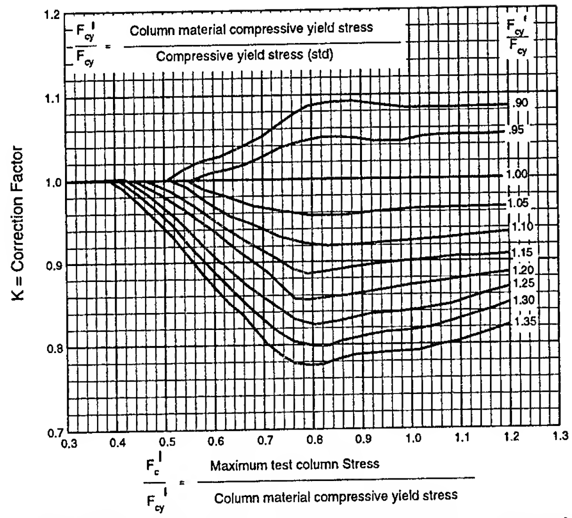

FIGURE 1.6.4.4(b). *Nondimensional material correction chart for 2024-T3 clad sheet.*

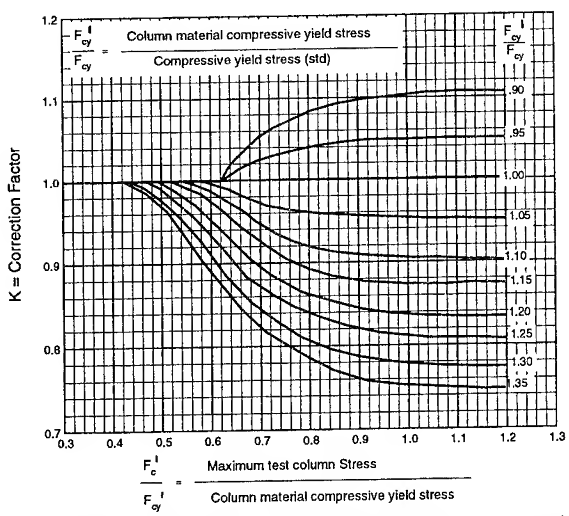

FIGURE 1.6.4.4(c). *Nondimensional material correction chart for 2024-T4 extrusion less than 1/4 inch thick.*

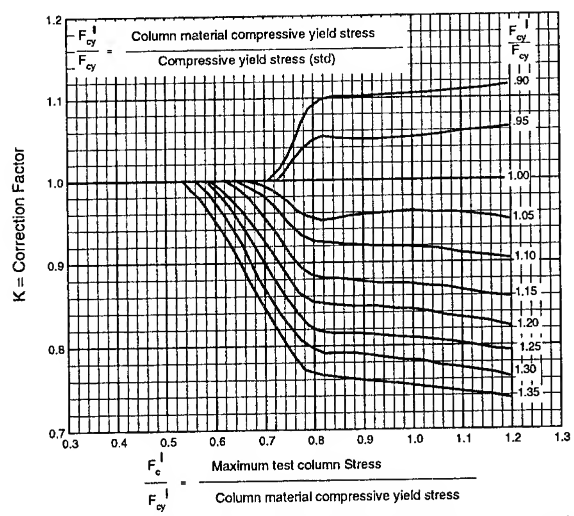

FIGURE 1.6.4.4(d). *Nondimensional material correction chart for 2024-T4 extrusion 1/4 to 1-1/2 inches thick.*

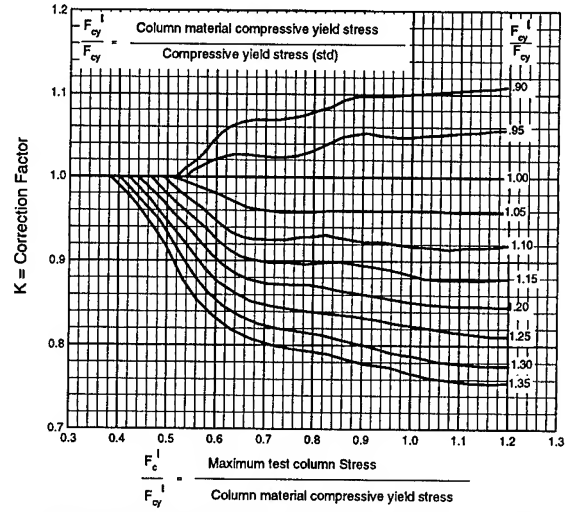

FIGURE 1.6.4.4(e). *Nondimensional material correction chart for 2024-T3 tubing.*

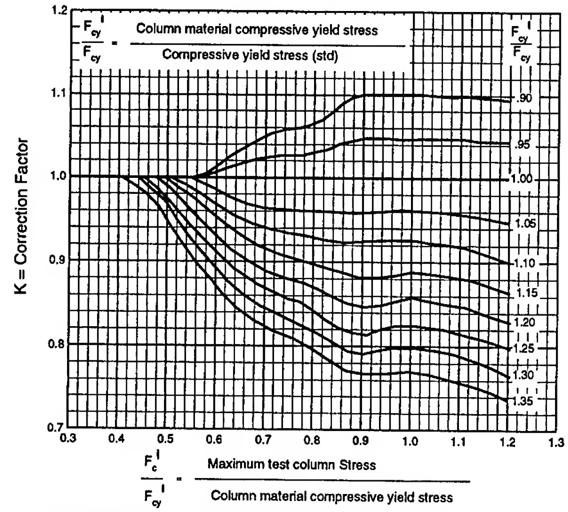

FIGURE 1.6.4.4(f). *Nondimensional material correction chart for clad 2014-T3 sheet.*

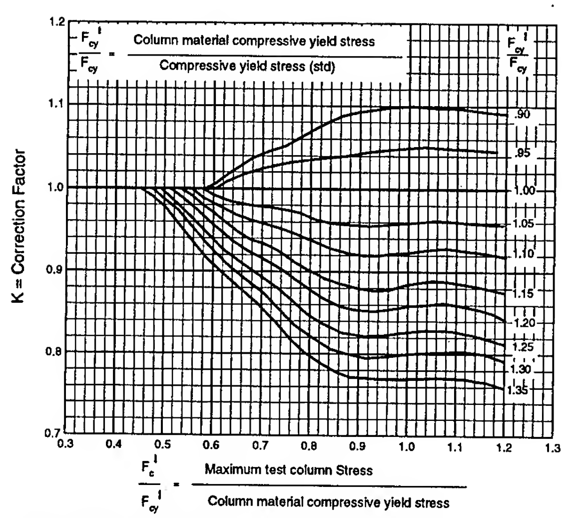

FIGURE 1.6.4.4(g). *Nondimensional material correction chart for 7075-T6 sheet.*

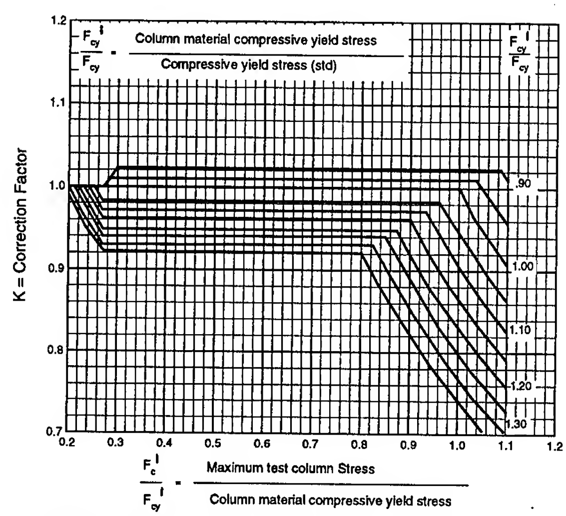

FIGURE 1.6.4.4(h). *Nondimensional material correction chart for AZ31B-F and AZ61A-F extrusion.*

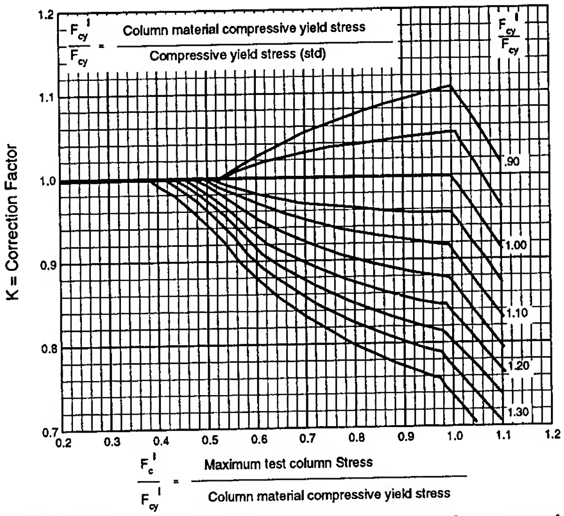

FIGURE 1.6.4.4(i). *Nondimensional material correction chart for AZ31B-H24 sheet.*

1.7 Thin-Walled and Stiffened Thin-Walled Sections

1.7.1 GENERAL.—A bibliography of information on thin-walled and stiffened thin-walled sections is contained in References 1.7.1(a) and (b).

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1.6.2.4(b) AFFDL-TR-69-42, "Stress Analysis Manual", Air Force Flight Dynamics Laboratory, Air Force Systems Command, Wright-Patterson Air Force Base (February 1970).

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Chapter 2

STEEL

This chapter contains the engineering properties and related characteristics of steels used in aircraft and missile structural applications. General comments on engineering properties and other considerations related to alloy selection are presented in Section 2.1. Mechanical and physical property data and characteristics pertinent to specific steel groups or individual steels are reported in Sections 2.2 through 2.7. Element properties are presented in Section 2.8.

2.1 General

The selection of the proper grade of steel for a specific application is based on material properties and on manufacturing, environmental, and economic considerations. Some of these considerations are outlined in the sections that follow.

2.1.1 ALLOY INDEX.—The steel alloys listed in this chapter are arranged in major sections that identify broad classifications of steel partly associated with major alloying elements, partly associated with processing, and consistent generally with steel-making technology. Specific alloys are identified as shown in Table 2.1.1.

2.1.2 MATERIAL PROPERTIES.—One of the major factors contributing to the general utility of steels is the wide range of mechanical properties which can be obtained by heat treatment. For example, softness and good ductility may be required during fabrication of a part and very high strength during its service life. Both sets of properties are obtainable in the same material.

All steels can be softened to a greater or lesser degree by annealing, depending on the chemical composition of the specific steel. Annealing is achieved by heating the steel to an appropriate temperature, holding, then cooling it at the proper rate.

Likewise, steels can be hardened or strengthened by means of cold working, heat treating, or a combination of these.

TABLE 2.1.1. *Steel Alloy Index*

Section	Alloy Designation
2.2	**Carbon steels**
2.2.1	AISI 1025
2.3	**Low-alloy steels (AISI and proprietary grades)**
2.3.1	Specific alloys
2.4	**Intermediate alloy steels**
2.4.1	5Cr-Mo-V
2.4.2	9Ni-4Co-0.20C
2.4.3	9Ni-4Co-0.30C
2.5	**High alloy steels**
2.5.1	18 Ni maraging steels
2.5.2	AF1410
2.6	**Precipitation and transformation hardening steel (stainless)**
2.6.1	AM-350
2.6.2	AM-355
2.6.3	Custom 450
2.6.4	Custom 455
2.6.5	PH13-8Mo
2.6.6	15-5PH
2.6.7	PH15-7Mo
2.6.8	17-4PH
2.6.9	17-7PH
2.7	**Austenitic stainless steels**
2.7.1	AISI Type 301

Cold working is the method used to strengthen both the low-carbon unalloyed steels and the highly alloyed austenitic stainless steels. Only moderately high strength levels can be attained in the former, but the latter can be cold rolled to quite high strength levels, or "tempers". These are commonly supplied to specified minimum strength levels.

Heat treating is the principal method for strengthening the remainder of the steels (the low-carbon steels and the austenitic steels cannot be strengthened by heat treatment). The heat treatment of steel may be of three types: martensitic hardening, age hardening, and austempering. Carbon and alloy steels are martensitic-hardened

by heating to a high temperature, or "austenitizing", and cooling at a recommended rate, often by quenching in oil or water. This is followed by "tempering", which consists of reheating to an intermediate temperature to relieve internal stresses and to improve toughness.

The maximum hardness of carbon and alloy steels, quenched rapidly to avoid the nose of the isothermal transformation curve, is a function in general of the alloy content, particularly the carbon content. Both the maximum thickness for complete hardening or the depth to which an alloy will harden under specific cooling conditions, and the distribution of hardness can be used as a measure of a material's hardenability.

A relatively new class of steels is strengthened by age hardening. This heat treatment is designed to dissolve certain constituents in the steel, then precipitate them in some preferred particle size and distribution. Since both the martensitic hardening and the age-hardening treatments are relatively complex, specific details are presented for individual steels elsewhere in this chapter.

Recently, special combinations of working and heat treating have been employed to further enhance the mechanical properties of certain steels. At the present time, the use of these specialized treatments is not widespread.

Another method of heat treatment for steels is austempering. In this process, ferrous steels are austenitized, quenched rapidly to avoid transformation of the austenite to a temperature below the pearlite and above the martensite formation ranges, allowed to transform isothermally at that temperature to a completely bainitic structure, and finally cooled to room temperature. The purpose of austempering is to obtain increased ductility or notch toughness at hard hardness levels, or to decrease the likelihood of cracking and distortion that might occur in conventional quenching and tempering.

2.1.2.1 *Mechanical Properties*

2.1.2.1.1 *Strength (Tension, Compression, Shear, Bearing)*.—The strength properties presented are those used in structural design. The room-temperature properties are shown in tables following the comments for individual steels. The variations in strength properties with temperature are presented graphically as percentages of the corresponding room-temperature strength property, also described in Section 9.3.1 and associated subsections. These strength properties may be reduced appreciably by prolonged exposure at elevated temperatures.

The strength of steels is temperature-dependent, decreasing with increasing temperature. In addition, steels are strain rate-sensitive above about 600 to 800 F, particularly at temperatures at which creep occurs. At lower strain rates, both yield and ultimate strengths decrease.

The modulus of elasticity is also temperature-dependent and, when measured by the slope of the stress-strain curve, it appears to be strain rate-sensitive at elevated temperatures because of creep during loading. However, on loading or unloading at high rates of strain, the modulus approaches the value measured by dynamic techniques.

Steel bars, billets, forgings, and thick plates, especially when heat treated to high strength levels, exhibit variations in mechanical properties with location and direction. In particular, elongation, reduction of area, toughness, and notched strength are likely to be lower in either of the transverse directions than in the longitudinal direction. This lower ductility and/or toughness results both from the fibering caused by the metal flow and from nonmetallic inclusions which tend to be aligned with the direction of primary flow. Such anisotropy is independent of the depth-of-hardening considerations discussed elsewhere. It can be minimized by careful control of melting practices (including degassing and vacuum-arc remelting) and of hot-working practices. In applications where transverse properties are critical, requirements should be discussed with the steel supplier and properties in critical locations should be substantiated by appropriate testing.

2.1.2.1.2 *Elongation*.—The elongation values presented in this chapter apply in both the longitudinal and long transverse directions, unless otherwise noted. Elongation in the short transverse (thickness) direction may be lower than the values shown.

2.1.2.1.3 *Fracture Toughness.*—Steels (as well as certain other metals), when processed to obtain high strength, or when tempered or aged within certain critical temperature ranges, may become more sensitive to the presence of small flaws. Thus, as discussed in Section 1.4.12, the usefulness of high-strength steels for certain applications is largely dependent on their toughness. It is generally noted that the fracture toughness of a given alloy product decreases relative to increase in the yield strength. The designer is cautioned that the propensity for brittle fracture must be considered in the application of high-strength alloys for the purpose of increased structural efficiency.

Minimum, average, and maximum values, as well as coefficient of variation of plane-strain fracture toughness for several steel alloys are presented in Table 2.1.2.1.3. These values are presented as indicative information and do not have the statistical reliability of room-temperature mechanical properties. Data showing the effect of temperature are presented in the respective alloy sections where the information is available.

2.1.2.1.4 *Stress-Strain Relationships.*—The stress-strain relationships presented in this chapter are prepared as described in Section 9.3.2.

2.1.2.1.5 *Fatigue.*—Axial-load fatigue data on unnotched and notched specimens of various steels at room temperature and at other temperatures are shown as S-N curves in the appropriate section. Surface finish, surface finishing procedures, metallurgical effects from heat treatment, environment and other factors influence fatigue behavior. Specific details on these conditions are presented as correlative information for the S/N curve.

2.1.2.2 *Physical Properties.*—The physical properties (ω, C, K, and α) of steels may be considered to apply to all forms and heat treatments unless otherwise indicated.

2.1.3 ENVIRONMENTAL CONSIDERATIONS.—The effects of exposure to environments such as stress, temperature, atmosphere, and corrosive media are reported for various steels. Fracture toughness of high-strength steels and the growth of cracks by fatigue may be detrimentally influenced by humid air and by the presence of water or saline solutions. Some alleviation may be achieved by heat treatment and all high-strength steels are not similarly affected.

In general, these comments apply to steels in their usual finished surface condition, without surface protection. It should be noted that there are available a number of heat-resistant paints, platings, and other surface coatings that are employed either to improve oxidation resistance at elevated temperature or to afford protection against corrosion by specific media. In employing electrolytic platings, special consideration should be given to the removal of hydrogen by suitable baking. Failure to do so may result lowered fracture toughness or embrittlement.

TABLE 2.1.2.1.3. *Values of Room Temperature Plane-Strain Fracture Toughness of Steel Alloys*[a]

Alloy	Heat Treat Condition	Product Form	Orientation[b]	Yield Strength Range, ksi	Product Thickness Range, inches	Number of Sources	Sample Size	Specimen Thickness Range, inches	K_{IC}, ksi $\sqrt{in.}$ Max.	Avg.	Min.	Coefficient of Variation.
D6AC	1650F, Aus-Bay Quench 975F, SQ 375F, 1000F 2+2	Plate	L-T	217	1.5	1	19	0.6	88	62	40	22.5
D6AC	1650F, Aus-Bay Quench 975F, SQ 400F, 1000F 2+2	Plate	L-T	217	0.8	1	103	0.6-0.8	92	64	44	18.9
D6AC	1650F, Aus-Bay Quench 975F, SQ 400F, 1000F 2+2	Forging	L-T	214	0.8-1.5	1	53	0.6-0.8	96	66	39	18.6
D6AC	1700F, Aus-Bay Quench 975F, OQ 140F, 1000F 2+2	Plate	L-T	217	0.8-1.5	1	30	0.6-0.8	101	92	64	8.9
D6AC	1700F, Aus-Bay Quench 975F, OQ 140F, 1000F 2+2	Forging	L-T	214	0.8-1.5	1	34	0.7	109	95	81	6.7
9Ni-4Co-.20C	Quench and Temper	Hand Forging	L-T	185-192	3.0	2	27	1.0-2.0	147	129	107	8.3
9Ni-4Co-.20C	1650F, 1-2 Hr, AC, 1525F, 1-2 Hr, OQ, -100F, Temp	Forging	L-T	186-192	3.0-4.0	3	17	1.5-2.0	147	134	120	8.5
PH13-8Mo	H1000	Forging	L-T	205-212	4.0-8.0	3	12	0.7-2.0	104	90	49	21.5

[a]These values are for information only.
[b]Refer to Figure 1.4.12.3 for definition of symbols.

2.2 Carbon Steels

2.2.0 COMMENTS ON CARBON STEELS

2.2.0.1 *Metallurgical Considerations.*—Carbon steels are those steels containing carbon up to about 1 percent and only residual quantities of other elements except those added for deoxidation.

The strength that carbon steels are capable of achieving is determined by carbon content and, to a much lesser extent, by the content of the residual elements. Through cold working or proper choice of heat treatments, these steels can be made to exhibit a wide range of strength properties.

The finish conditions most generally specified for carbon steels include hot-rolled, cold-rolled, cold-drawn, normalized, annealed, spheroidized, stress-relieved, and quenched-and-tempered. In addition, the low-carbon grades (up to 0.25 percent C) may be carburized to obtain high surface hardness and wear resistance with a tough core. Likewise, the higher carbon grades are amenable to selective flame hardening to obtain desired combinations of properties.

2.2.0.2 *Manufacturing Considerations*

Forging.—All of the carbon steels exhibit excellent forgeability in the austenitic state provided the proper forging temperatures are used. As the carbon content is increased, the maximum forging temperature is decreased. At high temperatures, these steels are soft and ductile and exhibit little or no tendency to work harden. The resulfurized grades (free-machining steels) exhibit a tendency to rupture when deformed in certain high-temperature ranges. Close control of forging temperatures is required.

Cold Forming.—The very low-carbon grades have excellent cold-forming characteristics when in the annealed or normalized conditions. Medium-carbon grades show progressively poorer formability with higher carbon content, and more frequent annealing is required. The high-carbon grades require special softening treatments for cold forming. Many carbon steels are embrittled by warm working or prolonged exposure in the temperature range from 300 to 700 F.

Machining.—The low-carbon grades (0.30 percent C and less) are soft and gummy in the annealed condition and are preferably machined in the cold-worked or the normalized condition. Medium-carbon (0.30 to 0.50 percent C) grades are best machined in the annealed condition, and high-carbon grades (0.50 to 0.90 percent C) in the spheroidized condition. Finish machining must often be done in the fully heat-treated condition for dimensional accuracy. The resulfurized grades are well known for their good machinability. Nearly all carbon steels are now available with 0.15 to 0.35 percent lead, added to improve machinability. However, resulfurized and leaded steels are not generally recommended for highly stressed aircraft and missile parts because of a drastic reduction in transverse properties.

Welding.—The low-carbon grades are readily welded or brazed by all techniques. The medium-carbon grades are also readily weldable but may require preheating and postwelding heat treatment. The high-carbon grades are difficult to weld. Preheating and postwelding heat treatment are usually mandatory for the latter, and special care must be taken to avoid overheating. Furnace brazing has been used successfully with all grades.

Heat Treatment.—Due to the poor oxidation resistance of carbon steels, protective atmospheres must be employed during heat treatment if scaling of the surface cannot be tolerated. Also, these steels are subject to decarburization at elevated temperatures and, where surface carbon content is critical, should be heated in reducing atmospheres.

2.2.0.3 *Environmental Considerations.*—Carbon steels have poor oxidation resistance above about 900 to 1000 F. Strength and oxidation-resistance criteria generally preclude the use of carbon steels above 900 F.

Carbon steels may undergo an abrupt transition from ductile to brittle behavior. This transition temperature varies widely for different carbon steels depending on many factors. Cautions should be exercised in the application of carbon steels to assure that the transition temperature of the selected alloy is below the service temperature. Additional information is contained in References 2.2.0.3(a) and (b).

The corrosion resistance of carbon steels is relatively poor; clean surfaces rust rapidly in moist atmospheres. Simple oil film protection is adequate for normal handling. For aerospace applications, the carbon steels are usually plated to provide adequate corrosion protection.

2.2.1 AISI 1025

2.2.1.0 *Comments and Properties.*—AISI 1025 is an excellent general purpose steel for the majority of shop requirements, including jigs, fixtures, prototype mockups, low torque shafting, and other applications. It is not generally classed as an airframe structural steel. However, it is available in aircraft quality as well as commercial quality.

Manufacturing Considerations.—Cold-finished flat-rolled products are supplied principally where maximum strength, good surface finish, or close tolerance is desirable. Reasonably good forming properties are found in AISI 1025. The machinability of bar stock is rated next to these sulfurized types of free-machining steels, but the resulting surface finish is poorer.

Specifications and Properties.—Material specifications for AISI 1025 steel are presented in Table 2.2.1.0(a). The room-temperature mechanical and physical properties are shown in Table 2.2.1.0(b). The effect of temperature on thermal expansion is shown in Figure 2.2.1.0.

TABLE 2.2.1.0(a). *Material Specifications for AISI 1025 Carbon Steel*

Specification	Form
MIL-S-7097, Comp. 3	Bar
AMS 5075	Seamless tubing
AMS 5077	Tubing
MIL-T-5066	Tubing
AMS 5046	Sheet, strip, and plate
MIL-S-7952,1025	Sheet and strip

TABLE 2.2.1.0(b). *Design Mechanical and Physical Properties of AISI 1025 Carbon Steel*

Specification	AMS 5046, Type 2, and MIL-S-7952, 1025	AMS 5075, AMS 5077, and MIL-T-5066	MIL-S-7097, Comp. 3
Form	Sheet, strip, and plate	Tubing	Bar
Condition	Annealed	Normalized	All
Thickness, in.	...	...	...
Basis	S	S	S
Mechanical Properties:			
F_{tu}, ksi:			
L	55	55	55
LT	55	55	55
ST	...	...	55
F_{ty}, ksi:			
L	36	36	36
LT	36	36	36
ST	...	...	36
F_{cy}, ksi:			
L	36	36	36
LT	36	36	36
ST	...	...	36
F_{su}, ksi	35	35	35
F_{bru}, ksi:			
(e/D = 1.5)	...	...	...
(e/D = 2.0)	90	90	90
F_{bry}, ksi:			
(e/D = 1.5)	...	...	...
(e/D = 2.0)	...	...	...
e, percent:			
L	...	a	a
LT	a	...	...
E, 10^3 ksi		29.0	
E_c, 10^3 ksi		29.0	
G, 10^3 ksi		11.0	
μ		0.32	
Physical Properties:			
ω, lb/in.^{3}		0.284	
C, Btu/(lb)(F)		0.116 (122 to 212 F)	
K, Btu/[(hr)(ft^2)(F)/ft]		30.0 (at 32 F)	
α, 10^{-6} in./in./F		See Figure 2.2.1.0	

[a]See applicable specification for variation in minimum elongation with ultimate strength.

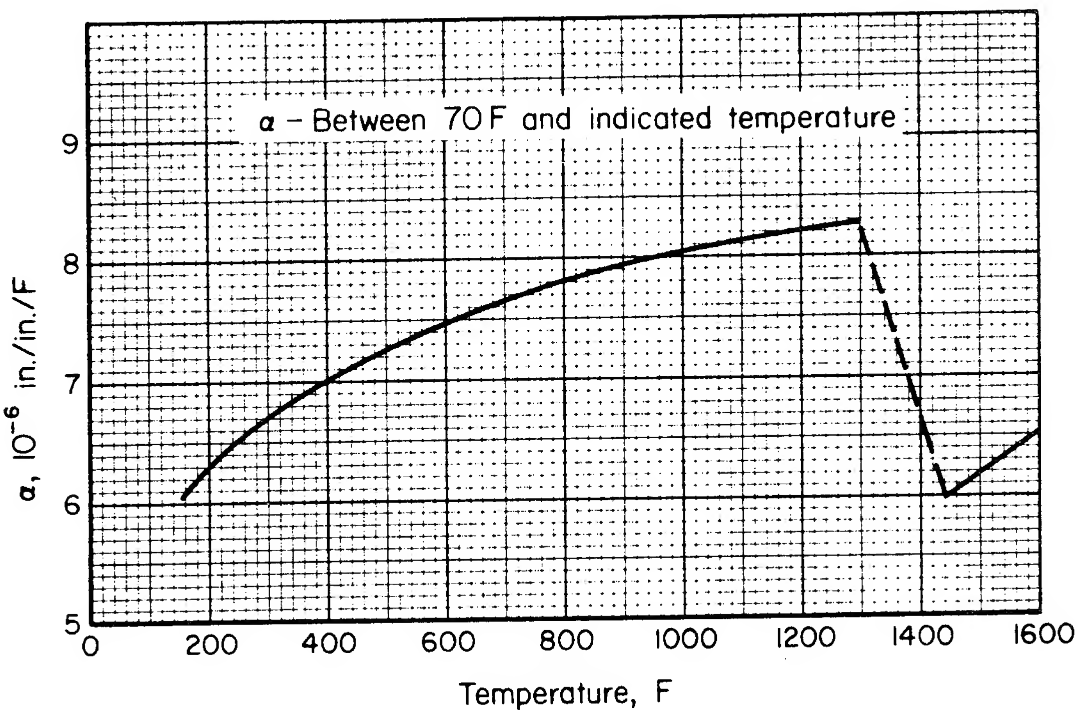


FIGURE 2.2.1.0. *Effect of temperature on the thermal expansion of 1025 steel.*

2.3 Low-Alloy Steels (AISI Grades and Proprietary Grades)

2.3.0 COMMENTS ON LOW-ALLOY STEELS (AISI AND PROPRIETARY GRADES)

2.3.0.1 *Metallurgical Considerations.*—The AISI or SAE alloy steels contain, in addition to carbon, up to about 1 percent (up to 0.5 percent for most airframe applications), additions of various alloying elements to improve their strength, depth of hardening, toughness, or other properties of interest. Generally, alloy steels have better strength-to-weight ratios than carbon steels and are somewhat higher in cost on a weight, but not necessarily strength, basis. Their applications in airframes include landing-gear components, shafts, gears, and other parts requiring high strength, through hardening, or toughness.

Some alloy steels are identified by the AISI four-digit system of numbers. The first two digits indicate the alloy group and the last two the approximate carbon content in hundredths of a percent. The alloying elements used in these steels include manganese, silicon, nickel, chromium, molybdenum, vanadium, and boron. Other steels in this section are proprietary steels which may be modifications of the AISI grades. The alloying additions in these steels may provide deeper hardening, higher strength and toughness.

These steels are available in a variety of finish conditions, ranging from hot- or cold-rolled to quenched-and-tempered. They are generally heat treated before use to develop the desired properties. Some steels in this group are carburized, then heat treated to produce a combination of high surface hardness and good core toughness.

2.3.0.2 *Manufacturing Conditions*

Forging.—The alloy steels are only slightly more difficult to forge than carbon steels. However, maximum recommended forging temperatures are generally about 50 F lower than for carbon steels of the same carbon content. Slower heating rates, shorter soaking period, and slower cooling rates are also required for alloy steels.

Cold Forming.—The alloy steels are usually formed in the annealed condition. Their formability depends mainly on the carbon content and is generally slightly poorer than for unalloyed steels of the same carbon content. Little cold forming is done on these steels in the heat-treated condition because of their high strength and limited ductility.

Machining.—The alloy steels are generally harder than unalloyed steels of the same carbon content. As a consequence, the low-carbon alloy steels are somewhat easier to finish machine than their counterparts in the carbon steels. It is usually desirable to finish machine the carburizing and through-hardening grades in the final heat-treated condition for better dimensional accuracy. This often leads to two steps in machining: rough machining in the annealed or hot-finished condition, then finish machining after heat treating. The latter operation, because of the relatively high hardness of the material, necessitates the use of sharp, well-designed, high-speed steel cutting tools, proper feeds, speeds, and a generous supply of coolant. Medium- and high-carbon grades are usually spheroidized for optimum machinability and, after heat treatment, may be finished by grinding. Many of the alloy steels are available with added sulfur or lead for improved machinability. However, resulfurized and leaded steels are not recommended for highly stressed aircraft and missile parts, because of drastic reductions in transverse properties.

Welding.—The low-carbon grades are readily welded or brazed by all techniques. Alloy welding rods comparable in strength to the base metal are used, and moderate preheating (200 to 600 F) is usually necessary. At higher carbon levels, higher preheating temperatures, and often post-welding stress relieving, are required. Certain alloy steels can be welded without loss of strength in the heat-affected zone provided that the welding heat input is carefully controlled. If the composition and strength level are such that the strength of the welded joint is reduced, the strength of the joint may be restored by heat treatment after welding.

Heat Treatment.—Maximum hardness in these steels is obtained in the as-quenched condition, but toughness and ductility in this condition are comparatively low. By means of tempering, their

toughness is improved, usually accompanied by a decrease in strength and hardness. In general, tempering temperatures to achieve very high strength should be avoided when toughness is an important consideration.

In addition, these steels may be embrittled by tempering or by prolonged exposure under stress within the "blue brittle" range (approximately 500 to 700 F). Strength levels that necessitate tempering within this range should be avoided.

The mechanical properties presented in this chapter represent steels heat treated to produce a quenched structure containing 90 percent martensite at the center and tempered to the desired F_{tu} level. This degree of through hardening is necessary (regardless of strength level) to insure the attainment of reasonably uniform mechanical properties throughout the cross section of the heat-treated part. The maximum diameter of round bars of various alloy steels capable of being through hardened consistently are given in Table 2.3.0.2. Limiting dimensions for common shapes other than round are determined by means of the "equivalent round" concept in Figure 2.3.0.2. This concept is essentially a correlation between the significant dimensions of a particular shape and the diameter of a round bar, assuming in each instance that the material, heat treatment, and the mechanical properties at the centers of both the respective shape and the equivalent round are substantially the same.

TABLE 2.3.0.2. *Maximum Round Diameters for Low-Alloy Steel Bars (Through Hardening to at Least 90 Percent Martensite at Center)*

	Diameter of Round or Equivalent Round, in.[a]						
F_{tu}, ksi	0.5	0.8	1.0	1.7	2.5	3.5	5.0
270 & 280	. . .	. . .	. . .	. . .	. . .	. . .	300M[c]
260	. . .	. . .	. . .	AISI 4340[b]	AISI 4340[c]	AISI 4340[d]	. . .
220	. . .	. . .	. . .	AMS Grades[be]	AMS Grades[ce]	D6AC[b]	D6AC[c]
200	. . .	AISI 8740	AISI 4140	AISI 4340[b] AMS Grades[be]	AISI 4340[c] AMS Grades[ce]	AISI 4340[d] D6AC[b]	D6AC[c]
≤180	AISI 4130 and 8630	AISI 8735 4135 and 8740	AISI 4140	AISI 4340[b] AMS Grades[be]	AISI 4340[c] AMS Grades[ce]	AISI 4340[d] D6AC[b]	D6AC[c]

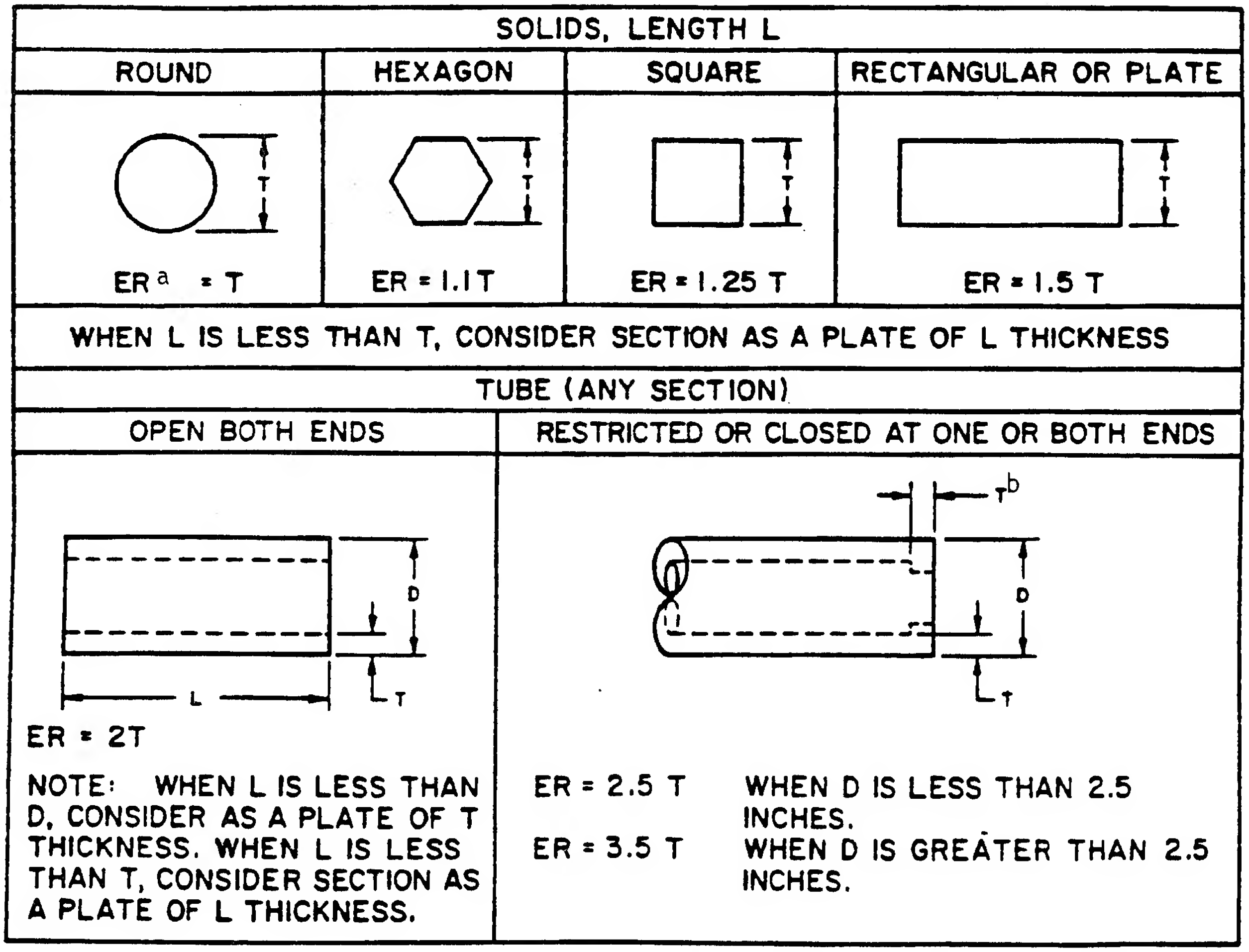
[a] This table indicates the maximum diameters to which these steels may be through hardened consistently by quenching as indicated. Any steels in this table may be used at diameters less than those indicated. The use of steels at diameters greater than those indicated should be based on hardenability data for specific heats of steel.

[b] Quenched in molten salt at desired tempering temperature ("martempering").

[c] Quenched in oil at a flow rate of 200 feet per minute.

[d] Quenched in water at a flow rate of 200 feet per minute.

[e] 4330 V, 4335 V, and Hy-Tuf.



[a]ER = equivalent round. (Illustration after MIL-H-6875.)
[b]Use maximum thickness for calculation.

FIGURE 2.3.0.2 *Correlation between significant dimensions of common shapes other than round, and the diameters of round bars.*

2.3.0.3 *Environmental Considerations.*—Alloy steels containing chromium or high percentages of silicon have somewhat better oxidation resistance than the carbon or other alloy steels. Elevated-temperature strength for the alloy steels is also higher than that of corresponding carbon steels. The mechanical properties of all alloy steels in the heat-treated condition are affected by extended exposure to temperatures near or above the temperature at which they were tempered. The limiting temperatures to which each alloy may be exposed for no longer than approximately 1 hour per inch of thickness or approximately one-half hour for thicknesses under one-half inch without a reduction in strength occurring are listed in Table 2.3.0.3. These values are approximately 100 F below typical tempering temperatures used to achieve the designated strength levels.

Low-alloy steels may undergo a transition from ductile to brittle behavior at low temperatures. This transition temperature varies widely for different alloys. Caution should be exercised in the application of low-alloy steels at temperatures below -100 F. For use at a temperature below -100 F, an alloy with a transition temperature below the service temperature should be selected. For low temperatures, the steel should be heat treated to a tempered martensitic condition for maximum toughness.

Heat-treated alloy steels have better notch toughness than carbon steels at equivalent strength levels. The decrease in notch toughness is less pronounced and occurs at lower temperatures. Heat-treated alloy steels may be useful for subzero applications, depending on their alloy content and heat treatment. Heat treating to strength levels higher than 150 ksi F_{ty} may decrease notch toughness.

The corrosion properties of the AISI alloy steels are comparable to the plain carbon steels.

TABLE 2.3.0.3. *Temperature Exposure Limits for Low-Alloy Steels*

	Exposure Limit, F						
F_{tu}, ksi	125	150	180	200	220	260	270 & 280
Alloy:							
AISI 4130 and 8630	925	775	575	...	...	...	...
AISI 4140 and 8740	1025	875	725	625	...	...	...
AISI 4340	1100	950	800	700	...	350	...
AISI 4135 and 8735	975	825	675	...	...	...	...
D6AC	1150	1075	1000	950	900	500	...
Hy-Tuf	875	750	650	550	450	...	...
4330V	925	850	775	700	500	...	...
4335V	975	875	775	700	500	...	...
300M	...	...	...	...	...	...	475

[a]Quenched and tempered to F_{tu} indicated. If the material is exposed to temperatures exceeding those listed, a reduction in strength is likely to occur.

2.3.1 SPECIFIC ALLOYS

2.3.1.0 *Comments and Properties.*—AISI 4130 is a chromium-molybdenum steel that is in general use due to its well established heat-treating practices and processing techniques. It is available in all sizes of sheet, plate, and tubing. Bar stock of this material is also used for small forgings under one-half inch in thickness. AISI 4135, a slightly higher carbon version of AISI 4130, is available in sheet, plate, and tubing.

AISI 4140 is a chromium-molybdenum steel that can be heat treated to higher strength levels or in thicker sections than AISI 4130. This steel is generally used for structural machined and forged parts one-half inch and over in thickness. It can be welded but it is more difficult to weld than the lower carbon grade AISI 4130.

AISI 4340 is a nickel-chromium-molybdenum steel that can be heat treated to higher strength levels or in thicker sections than AISI 4140.

AISI 8630, 8735, and 8740 are nickel-chromium-molybdenum steels that are considered alternates to AISI 4130, 4135, and 4140, respectively.

There are available a number of steels the compositions of which represent modifications of the AISI grades described above. Four of these steels which have been used rather extensively at F_{tu} = 220 ksi include D6AC, Hy-Tuf, 4330V, and 4335V. It should be noted that this strength level is not used for AISI 4340 due to embrittlement encountered during tempering in the range of 500 to 700 F. In addition, AISI 4340 and 300M are utilized at strength levels of F_{tu} = 260 ksi or higher. The alloys, AISI 4340, D6AC, 4330V, 4335V, and 300M, are available in the consumable electrode melted grade.

Material specifications for the steels are presented in Tables 2.3.1.0(a) and (b).

The room-temperature mechanical and physical properties for these steels are presented in Tables 2.3.1.0(c) through 2.3.1.0(g). Mechanical properties for heat-treated materials are valid only for steel heat treated to produce a quenched structure containing 90 percent or more martensite at the center. Figure 2.3.1.0 contains elevated temperature curves for the physical properties of AISI 4130 and AISI 4340 steels.

2.3.1.1 *AISI Low-Alloy Steels.*—Elevated temperature curves for heat-treated AISI low-alloy steels are presented in Figures 2.3.1.1.1 through 2.3.1.1.4. These curves are considered valid for each of these steels in each heat-treated condition but only up to the maximum temperatures listed in Table 2.3.0.1(b).

2.3.1.2 *AISI 4130 and 8630 Steels.*—Typical stress-strain and tangent-modulus curves for AISI 8630 are shown in Figures 2.3.1.2.6(a) through (c). Best-fit S/N curves for AISI 4130 steel are presented in Figures 2.3.1.2.8(a) through (h).

2.3.1.3 *AISI 4340 Steel.*—Typical stress-strain and tangent-modulus curves for AISI 4340 are shown in Figures 2.3.1.3.6(a) through (c). Typical biaxial stress-strain curves and yield-stress envelopes for AISI 4340 alloy steel are presented in Figures 2.3.1.3.6(d) through (g). Best-fit S/N curves for AISI 4340 are presented in Figures 2.3.1.3.8(a) through (o).

2.3.1.4 *300M Steel.*—Best-fit S/N curves for 300M steel are presented in Figures 2.3.1.4.8(a) through (d). Fatigue-crack-propagation data for 300M are shown in Figure 2.3.1.4.9.

2.3.1.5 *D6AC Steel.*—Fatigue-crack-propagation data for D6AC steel are presented in Figure 2.3.1.5.9.

TABLE 2.3.1.0(a). *Material Specifications for Air Melted Low-Alloy Steels*

Alloy	Form		
	Sheet, strip, and plate	Bars and forgings	Tubing
4130	MIL-S-18729, AMS 6350, AMS 6351	MIL-S-6758, AMS 6348, AMS 6370	MIL-T-6736, AMS 6371, AMS 6360, AMS 6361, AMS 6362, AMS 6373
8630	MIL-S-18728, AMS 6355	MIL-S-6050, AMS 6280	AMS 6281
4135	AMS 6352	...	AMS 6372, AMS 6365 MIL-T-6735
8735	AMS 6357	AMS 6320	AMS 6282
4140	AMS 6395	MIL-S-5626, AMS 6382, AMS 6349	AMS 6381, AMS 6390
4340	AMS 6359	MIL-S-5000, AMS 6415	AMS 6415
8740	AMS 6358	MIL-S-6049, AMS 6327, AMS 6322	AMS 6323
4330V	...	AMS 6427	AMS 6427
Hy-Tuf	...	AMS 6418	AMS 6418
4335V	AMS 6433	AMS 6430	AMS 6430

TABLE 2.3.1.0(b). *Material Specifications for Consumable Electrode Melted Low-Alloy Steels*

Alloy	Form		
	Sheet, strip, and plate	Bar and forgings	Tubing
4340	AMS 6454	MIL-S-8844, AMS 6414	MIL-S-8844, AMS 6414
D6AC	MIL-S-8949	MIL-S-8949, AMS 6431	AMS 6431
4330V	...	AMS 6411	AMS 6411
Hy-Tuf	...	AMS 6425	AMS 6425
4335V	AMS 6435	AMS 6429	AMS 6429
300M (0.40C)	...	AMS 6417	AMS 6417
300M (0.42C)	...	AMS 6419, MIL-S-8844 AMS 6257	AMS 6419, MIL-S-8844 AMS 6257

TABLE 2.3.1.0(c). *Design Mechanical and Physical Properties of Low-Alloy Steels*

Alloy [For specification see Tables 2.3.1.0(a) and (b)] ...	AISI 4130, 4135, 8630, and 8735		See steels listed in Table 2.3.0.2 for the applicable strength levels					
Form ...	Sheet, strip, plate, and tubing		All wrought forms					
Condition ...	N		Quenched and tempered[a]					
Thickness or diameter, in. ...	≤0.187	>0.187	See Table 2.3.0.2					
Basis ...	S	S	S	S	S	S	S	S
Mechanical Properties:								
F_{tu}, ksi ...	95	90	125	140	150	160	180	200
F_{ty}, ksi ...	75	70	100	120	132	142	163	176
F_{cy}, ksi ...	75	70	109	131	145	154	173	181
F_{su}, ksi ...	57	54	75	84	90	96	108	120
F_{bru}, ksi:								
(e/D = 1.5) ...	...	...	194	209	219	230	250	272
(e/D = 2.0) ...	200	190	251	273	287	300	326	355
F_{bry}, ksi:								
(e/D = 1.5) ...	...	...	146	173	189	202	230	255
(e/D = 2.0) ...	129	120	175	203	218	231	256	280
e, percent ...	See Table 2.3.1.0(d)		See Table 2.3.1.0(e)					
E, 10^3 ksi ...	29.0							
E_c, 10^3 ksi ...	29.0							
G, 10^3 ksi ...	11.0							
μ ...	0.32							
Physical Properties:								
ω, lb/in.^{3} ...	0.283							
C, K, and α ...	See Figure 2.3.1.0							

[a]Design values are applicable only to parts for which the indicated F_{tu} has been substantiated by adequate quality control testing.

TABLE 2.3.1.0(d). *Minimum Elongation Values for Low-Alloy Steels in Condition N*

Form	Thickness, in.	Elongation, percent	
		Full tube	Strip
Sheet, strip, and plate (T)	Less than 0.062	--	8
	Over 0.062 to 0.125 incl.	--	10
	Over 0.125 to 0.187 incl.	--	12
	Over 0.187 to 0.249 incl.	--	15
	Over 0.249 to 0.749 incl.	--	16
	Over 0.749 to 1.500 incl.	--	18
Tubing (L)	Up to 0.035 incl. (wall)	10	5
	Over 0.035 to 0.188 incl.	12	7
	Over 0.188	15	10

TABLE 2.3.1.0(e). *Minimum Elongation Values for Heat-Treated Low-Alloy Steels*

F_{tu}, ksi	Round specimens (L)		Elongation in 2 in., percent				
			Sheet specimens			Tubing (L)	
	Elongation in 4D, percent	Reduction of area, percent	Less than 0.032 in. thick	0.032 to 0.060 in. thick	Over 0.060 in. thick	Full tube	Strip
125	17	55	5	7	10	12	7
140	15	53	4	6	9	10	6
150	14	52	4	6	9	10	6
160	13	50	3	5	8	9	6
180	12	47	3	5	7	8	5
200	10	43	3	4	6	6	5

TABLE 2.3.1.0(f). *Design Mechanical and Physical Properties of Low-Alloy Steels*

Alloy [For specification see Tables 2.3.1.0(a) and (b)]	Hy-Tuf 4330V	D6AC 4335V	AISI 4340[a]	0.40C 300M	0.42C 300M
Form	All wrought forms		Bar, forging, tubing		
Condition	Quenched and tempered[b]		Quenched and tempered[b]		
Thickness or diameter, in.	See Table 2.3.0.2		See Table 2.3.0.2		
Basis	S	S	S	S	S
Mechanical Properties:					
F_{tu}, ksi	220	220	260	270	280
F_{ty}, ksi	185	190	217	220	230
F_{cy}, ksi	193	198	235	236	247
F_{su}, ksi	132	132	156	162	168
F_{bru}, ksi:					
(e/D = 1.5)	297	297	347	414[c]	430[c]
(e/D = 2.0)	385	385	440	506[c]	525[c]
F_{bry}, ksi:					
(e/D = 1.5)	267	274	312	344[c]	360[c]
(e/D = 2.0)	294	302	346	379[c]	396[c]
e, percent:					
L	10	[d]	10	8	7
LT	5[a]	[d]	...	...	...
E, 10^3 ksi	29.0				
E_c, 10^3 ksi	29.0				
G, 10^3 ksi	11.0				
μ	0.32				
Physical Properties:					
ω, lb/in.^{3}	0.283				
C, K, and α	See Figure 2.3.1.0				

[a]Applicable to consumable-electrode vacuum-melted material only.
[b]Design values are applicable only to parts for which the indicated F_{tu} has been substantiated by adequate quality control testing.
[c]Bearing values are "dry pin" values per Section 1.4.7.1.
[d]See Table 2.3.1.0(g) for elongation applicable to consumable-electrode vacuum-melted D6AC.

TABLE 2.3.1.0(g). *Minimum Elongation Values for Heat-Treated Consumable-Electrode Vacuum-Melted D6AC at F_{tu} = 220 ksi*

Form	Size	Elongation, percent	
		L	T
Bar and forging	≤ 50 sq in.	12	10
	> 50, ≤ 200 sq in.	12	8
	> 200 sq in.	10	7
Sheet and plate	< 5/8 in.	10	8

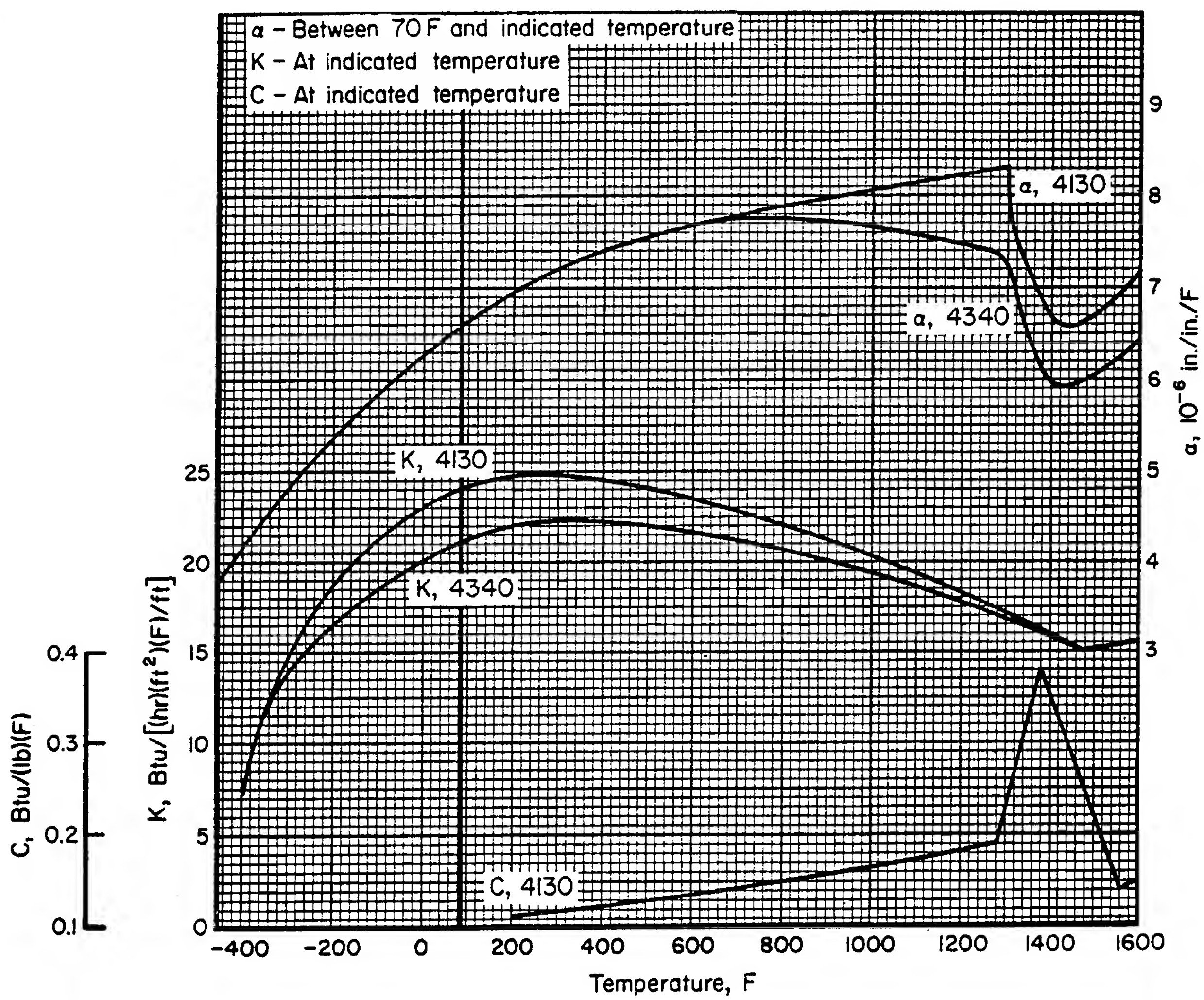


FIGURE 2.3.1.0. *Effect of temperature on the physical properties of 4130 and 4340 alloy steels.*

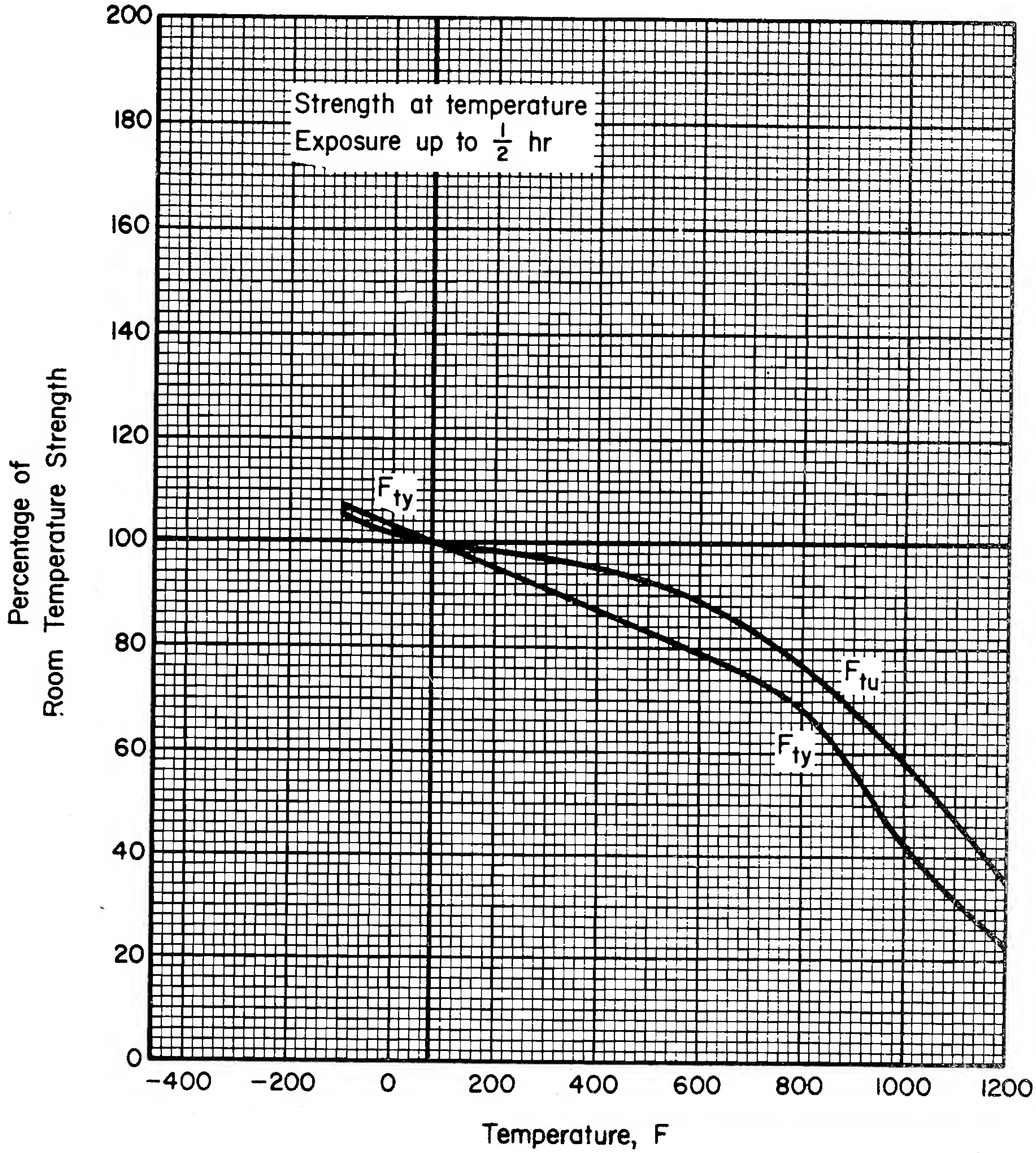


FIGURE 2.3.1.1.1. *Effect of temperature on the tensile ultimate strength (F_{tu}) and tensile yield strength (F_{ty}) of AISI low-alloy steels (all products).*

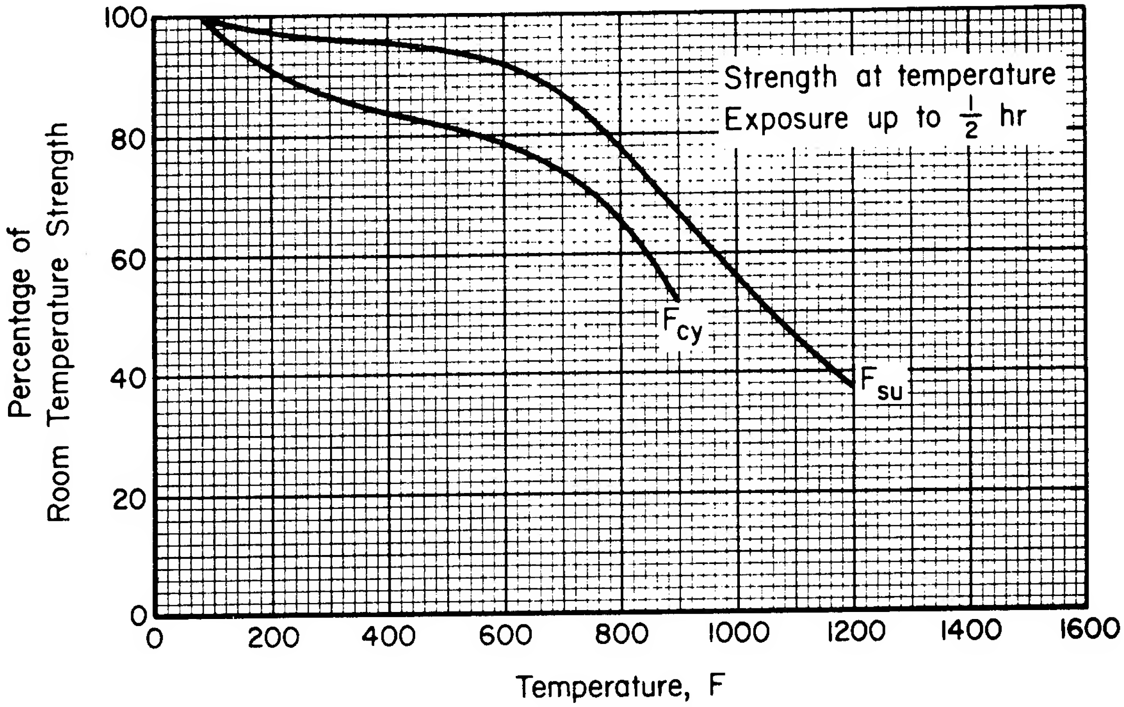


FIGURE 2.3.1.1.2. *Effect of temperature on the compressive yield strength (F_{cy}) and the shear ultimate strength (F_{su}) of heat-treated AISI low-alloy steels (all products).*

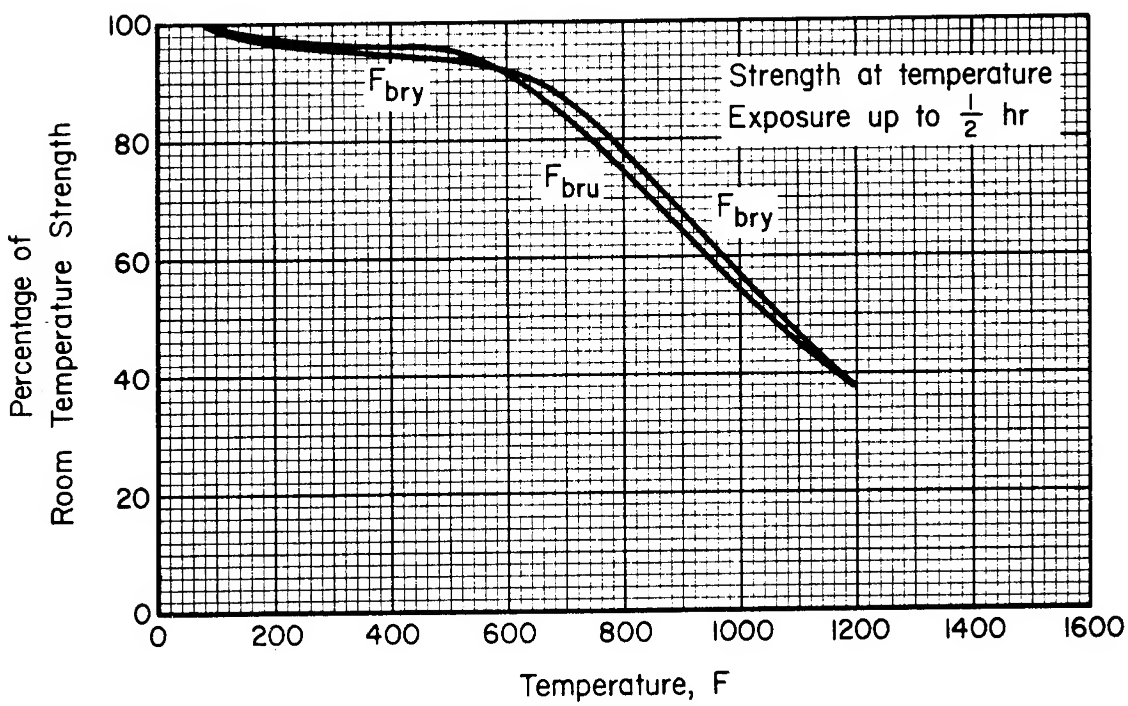


FIGURE 2.3.1.1.3. *Effect of temperature on the bearing ultimate strength (F_{bru}) and the bearing yield strength (F_{bry}) of heat-treated AISI low-alloy steels (all products).*

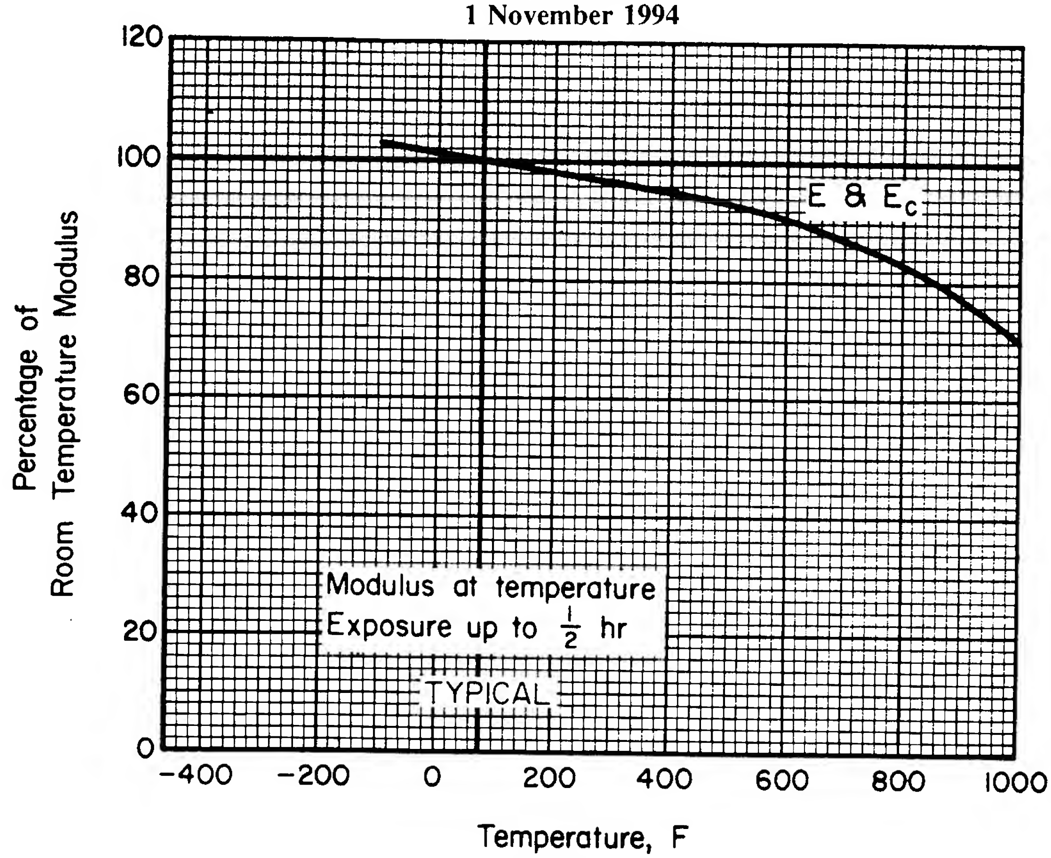


FIGURE 2.3.1.1.4. *Effect of temperature on the tensile and compressive modulus (E and E_c) of AISI low-alloy steels.*

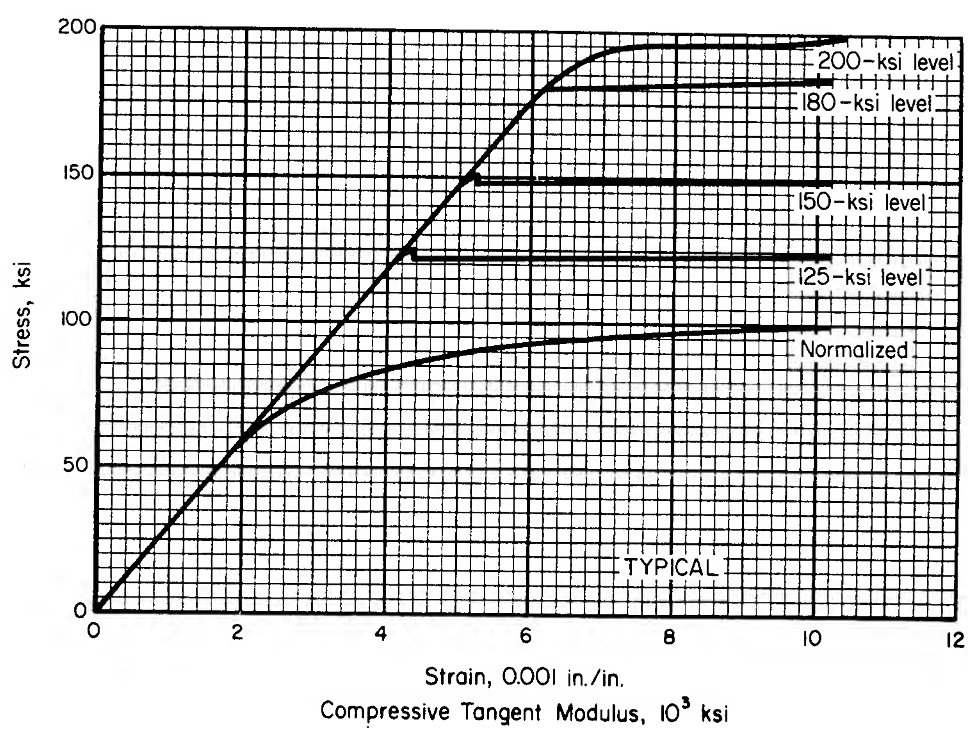


FIGURE 2.3.1.2.6(a). *Typical tensile stress-strain curves at room temperature for heat-treated AISI 8630 alloy steel (all products).*

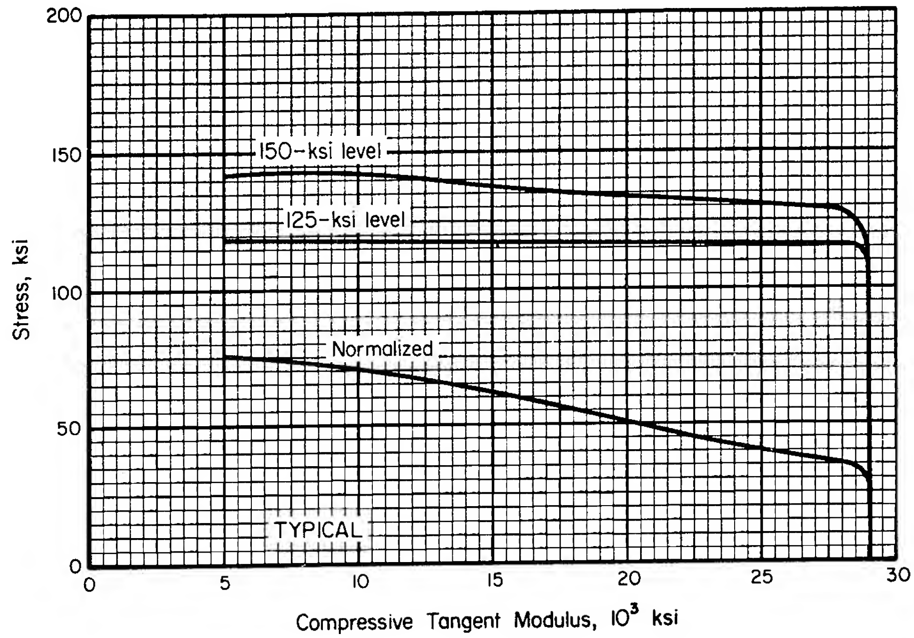


FIGURE 2.3.1.2.6(b). *Typical compressive tangent-modulus curves at room temperature for heat-treated AISI 8630 alloy steel (all products).*

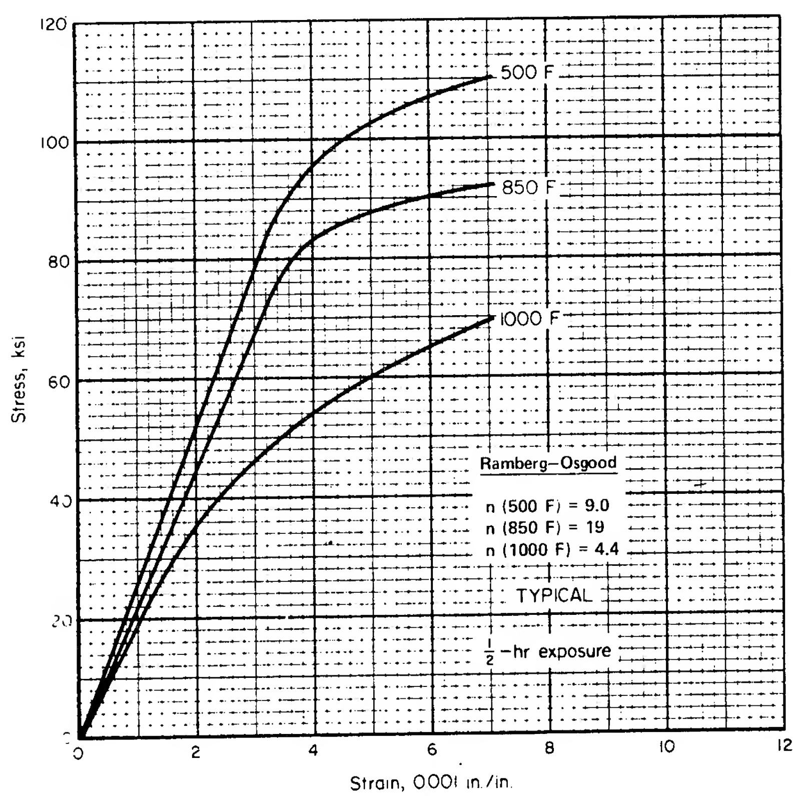


FIGURE 2.3.1.2.6(c). *Typical tensile stress-strain curves at elevated temperatures for heat-treated AISI 8630 alloy steel, F_{tu} = 125 ksi (all products).*

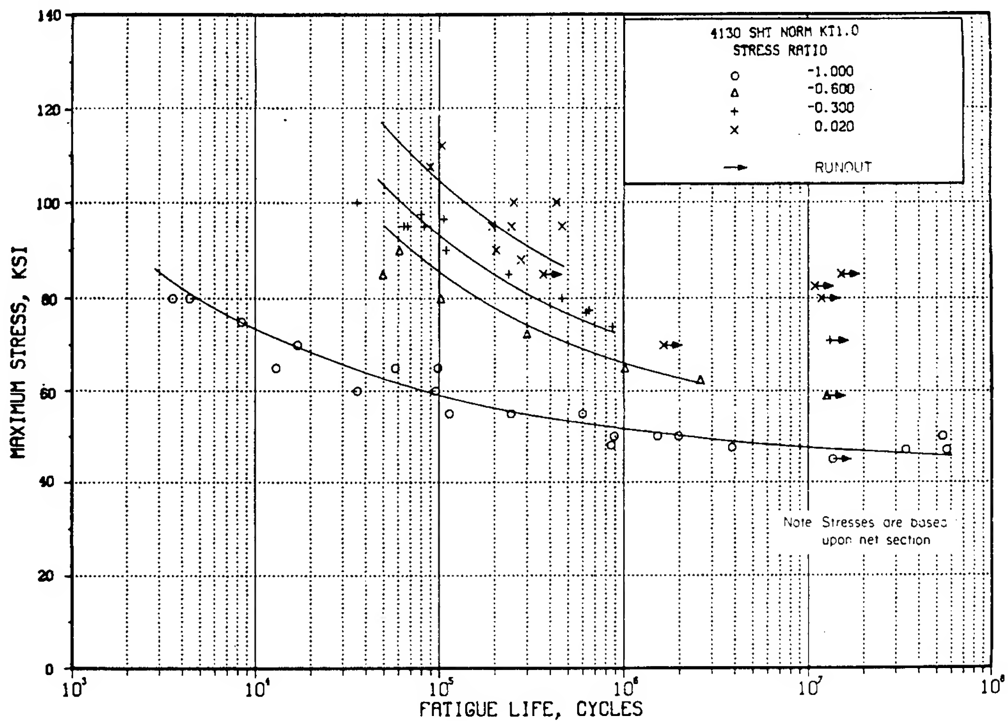


FIGURE 2.3.1.2.8(a). *Best-fit S/N curves for unnotched 4130 alloy steel sheet, normalized, longitudinal direction.*

Correlative Information for Figure 2.3.1.2.8(a)

Product Form: Sheet, 0.075-inch thick

Properties:	TUS, ksi	TYS, ksi	Temp., F
	117	99	RT

Specimen Details: Unnotched
2.88–3.00 inches gross width
0.80–1.00 inch net width
12.0 inch net section radius

Surface Condition: Electropolished

References: 3.2.3.1.8(a) and (f)

[Caution: The equivalent stress model may provide unrealistic life predictions for stress ratios beyond those represented above]

Test Parameters:

Loading – Axial
Frequency – 1100–1800 cpm
Temperature – RT
Environment – Air

No. of Heats/Lots: Not specified

Equivalent Stress Equations:

For stress ratios of -0.60 to +0.02

Log N_f = 9.65–2.85 log (S_{eq}–61.3)
$S_{eq} = S_{max} (1\text{-}R)^{0.41}$
Standard Error of Estimate = 0.21
Standard Deviation in Life = 0.45
R^2 = 78%

Sample Size = 23

For a stress ratio of -1.0

Log N_f = 9.27–3.57 log (S_{max}– 43.3)

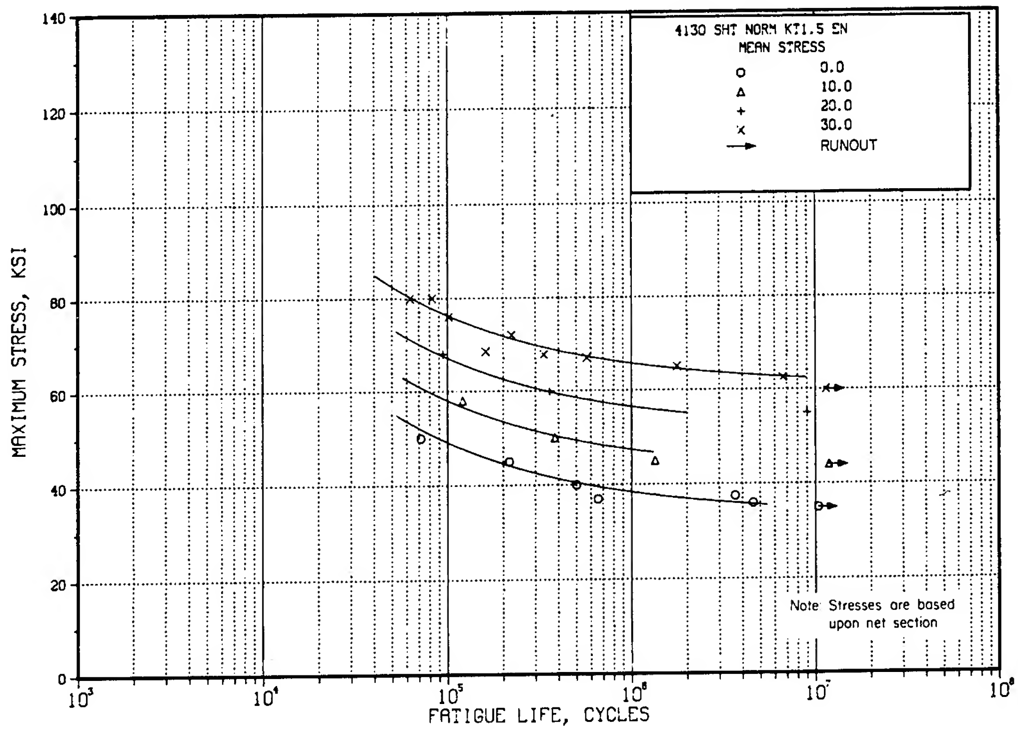


FIGURE 2.3.1.2.8(b). *Best-fit S/N curves for notched, K_t = 1.5, 4130 alloy steel sheet, normalized, longitudinal direction.*

Correlative Information for Figure 2.3.1.2.8(b)

Product Form: Sheet, 0.075-inch thick

Properties:	TUS, ksi	TYS, ksi	Temp., F
	117	99	RT (unnotched)
	123	—	RT (notched K_t 1.5)

Specimen Details: Edge Notched, K_t = 1.5
3.00 inches gross width
1.50 inches net width
0.76 inch notch radius

Surface Condition: Electropolished

Reference: 3.2.3.1.8(d)

Test Parameters:

Loading – Axial
Frequency – 1100 to 1500 cpm
Temperature – RT
Environment – Air

No. of Heats/Lots: Not specified

Equivalent Stress Equation:

Log N_f = 7.94–2.01 log (S_{eq}–61.3)
$S_{eq} = S_{max}\ (1\text{-}R)^{0.88}$
Standard Error Estimate = 0.27
Standard Deviation in Life = 0.67
R^2 = 84%

Sample Size = 21

[Caution: The equivalent stress model may provide unrealistic life predictions for stress ratios beyond those represented above]

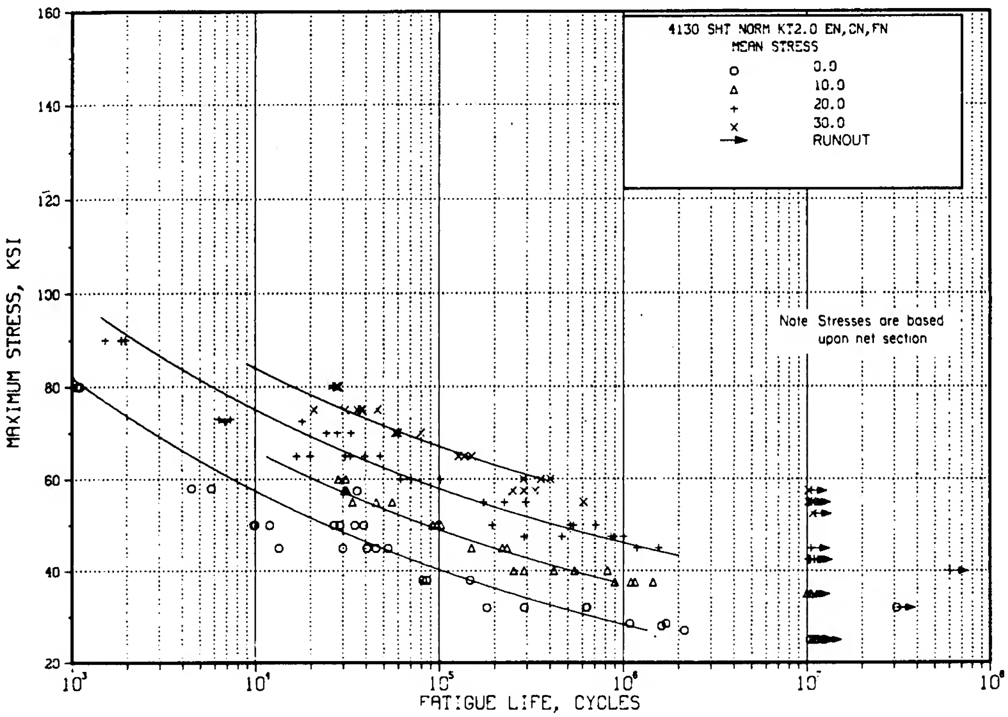


FIGURE 2.3.1.2.8(c). *Best-fit S/N curves for notched, K_t = 2.0, 4130 alloy steel sheet, normalized, longitudinal direction.*

Correlative Information for Figure 2.3.1.2.8(c)

Product Form: Sheet, 0.075-inch thick

Properties:

	TUS, ksi	TYS, ksi	Temp., F
	117	99	RT (unnotched)
	120	—	RT (notched) K_t = 2.0

Specimen Details: Notched K_t = 2.0

Notch Type	Gross Width	Net Width	Notch Radius
Edge	2.25	1.500	0.3175
Center	4.50	1.500	1.500
Fillet	2.25	1.500	0.1736

Surface Condition: Electropolished

References: 3.2.3.1.8(b) and (f)

Test Parameters:

Loading - Axial
Frequency - 1100-1800 cpm
Temperature - RT
Environment - Air

No. of Heats/Lots: Not specified

Equivalent Stress Equation:

Log N_f = 17.1-6.49 log (S_{eq})
$S_{eq} = S_{max} (1-R)^{0.86}$
Standard Error of Estimate = 0.19
Standard Deviation in Life = 0.78
R^2 = 94%

Sample Size = 107

[Caution: The equivalent stress model may provide unrealistic life predictions for stress ratios beyond those represented above]

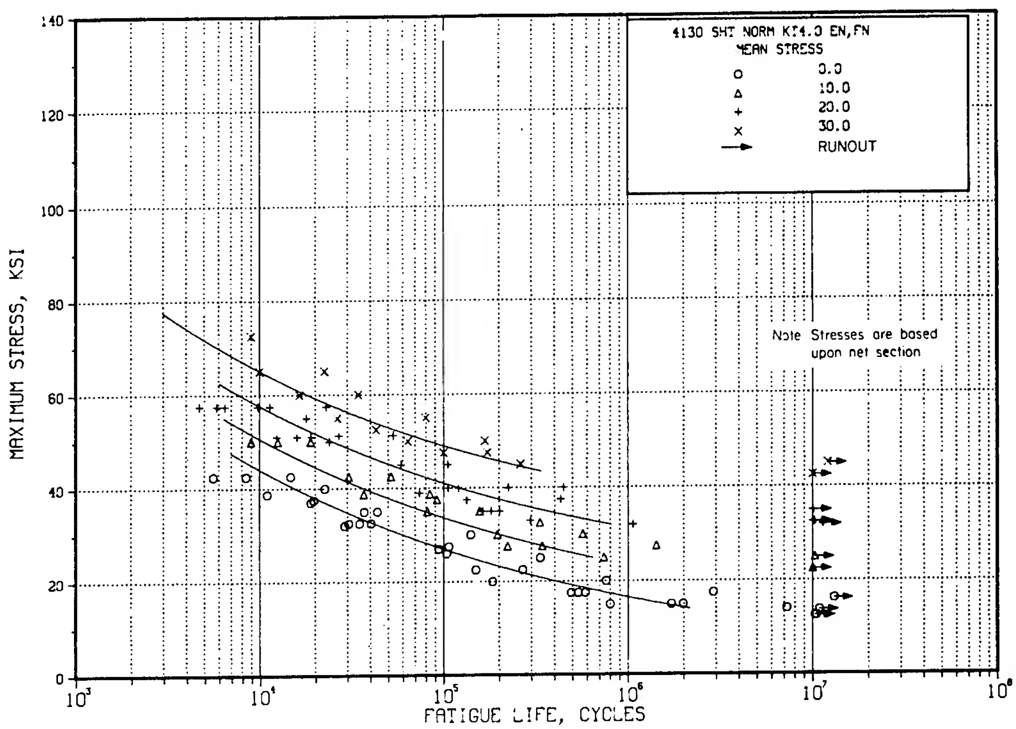


FIGURE 2.3.1.2.8(d). *Best-fit S/N curves for notched, $K_t = 4.0$, 4130 alloy steel sheet, normalized, longitudinal direction.*

Correlative Information for Figure 2.3.1.2.8(d)

Product Form: Sheet, 0.075-inch thick

Properties:	TUS, ksi	TYS, ksi	Temp., F
	117	99	RT (unnotched)
	120	—	RT (notched) $K_t = 4.0$

Specimen Details: Notched $K_t = 4.0$

Notch Type	Gross Width	Net Width	Notch Radius
Edge	2.25	1.500	0.057
Edge	4.10	1.496	0.070
Fillet	2.25	1.500	0.0195

Surface Condition: Electropolished

References: 3.2.3.1.8(b), (f), and (g)

Test Parameters:

Loading - Axial
Frequency - 1100–1800 cpm
Temperature - RT
Environment - Air

No. of Heats/Lots: Not specified

Equivalent Stress Equation:

$\text{Log } N_f = 12.6 - 4.69 \log (S_{eq})$
$S_{eq} = S_{max} (1-R)^{0.63}$
Standard Error of Estimate = 0.24
Standard Deviation in Life = 0.70
$R^2 = 88\%$

Sample Size = 87

[Caution: The equivalent stress model may provide unrealistic life predictions for stress ratios beyond those represented above]

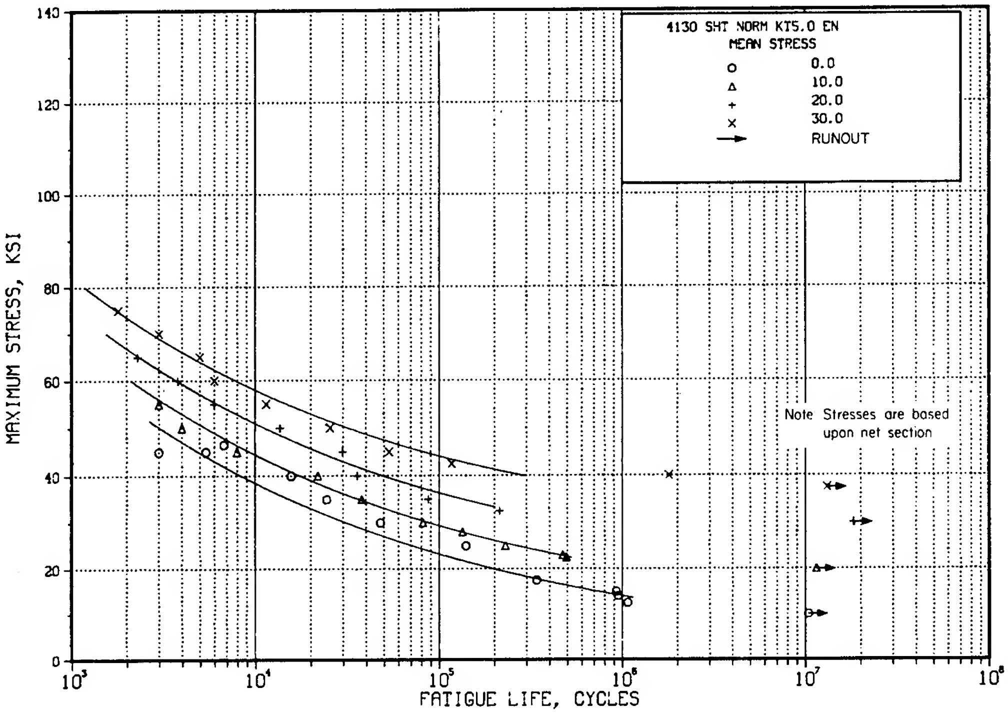


FIGURE 2.3.1.2.8(e). *Best-fit S/N curves diagram for notched, K_t = 5.0, 4130 alloy steel sheet, normalized, longitudinal direction.*

Correlative Information for Figure 2.3.1.2.8(e)

Product Form: Sheet, 0.075-inch thick

Properties:	TUS, ksi	TYS, ksi	Temp., F
	117	99	RT (unnotched)
	120	—	RT (notched K_t = 5.0)

Specimen Details: Edge Notched, K_t = 5.0
Gross width = 2.25 inches
Net width = 1.50 inches
Notch radius = 0.075 inch

Surface Condition: Electropolished

Reference: 3.2.3.1.8(c)

Test Parameters:

Loading - Axial
Frequency - 1100-1500 cpm
Temperature - RT
Environment - Air

No. of Heats/Lots: Not specified

Equivalent Stress Equation:

Log N_f = 12.0-4.57 log (S_{eq})
$S_{eq} = S_{max} (1-R)^{0.56}$
Standard Error of Estimate = 0.18
Standard Deviation in Life = 0.87
R^2 = 96%

Sample Size = 38

[Caution: The equivalent stress model may provide unrealistic life predictions for stress ratios beyond those represented above]

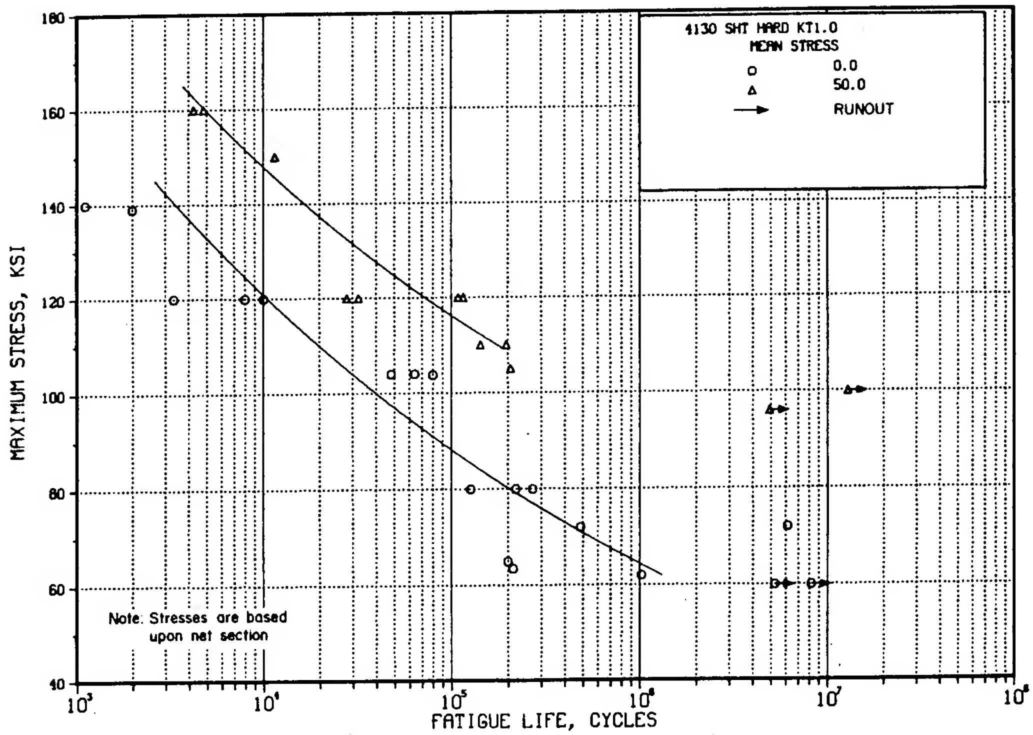


FIGURE 2.3.1.2.8(f). *Best-fit S/N curves for unnotched 4130 alloy steel sheet, F_{tu} = 180 ksi, longitudinal direction.*

Correlative Information for Figure 2.3.1.2.8(f)

Product Form: Sheet, 0.075-inch thick

Properties:	TUS, ksi	TYS, ksi	Temp., F
	180	174	RT

Specimen Details: Unnotched
2.88 inches gross width
1.00 inch net width
12.0 inch net section radius

Surface Condition: Electropolished

Reference: 3.2.3.1.8(f)

Test Parameters:

Loading - Axial
Frequency - 20-1800 cpm
Temperature - RT
Environment - Air

No. of Heats/Lots: Not specified

Equivalent Stress Equation:

Log N_f = 20.3-7.31 log (S_{eq})
$S_{eq} = S_{max}\ (1\text{-}R)^{0.49}$
Standard Error of Estimate = 0.39
Standard Deviation in Life = 0.89
R^2 = 81%

Sample Size = 27

[Caution: The equivalent stress model may provide unrealistic life predictions for stress ratios beyond those represented above]

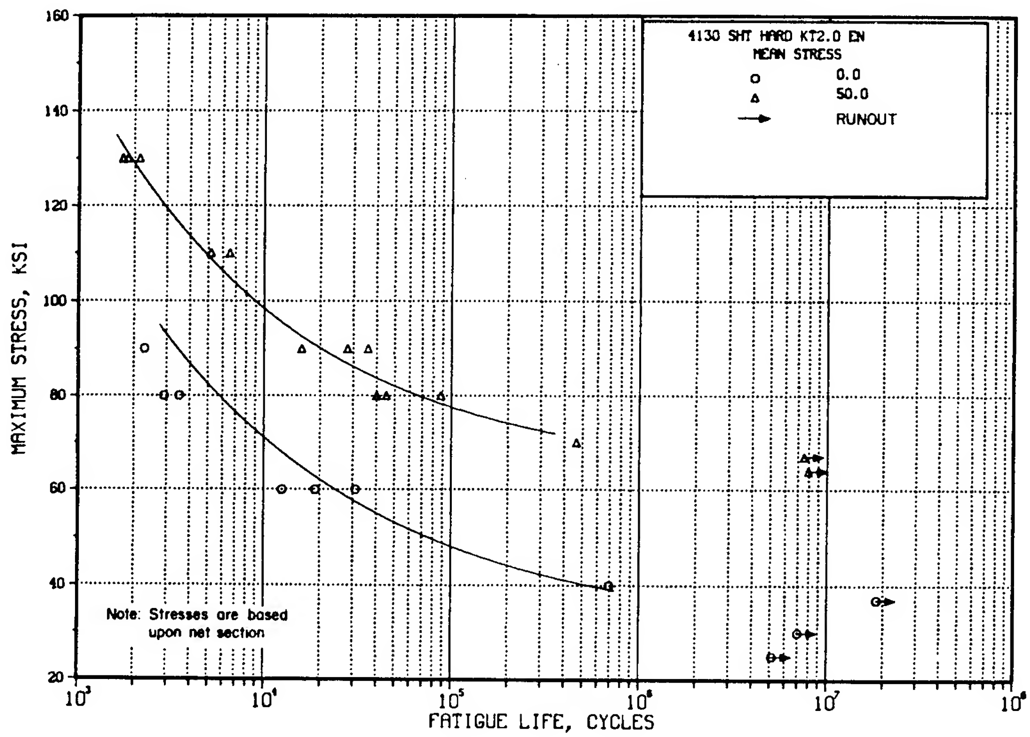


FIGURE 2.3.1.2.8(g). *Best-fit S/N curves for notched, K_t = 2.0, 4130 alloy steel sheet, F_{tu} = 180 ksi, longitudinal direction.*

Correlative Information for Figure 2.3.1.2.8(g)

Product Form: Sheet, 0.075-inch thick

Properties:

TUS, ksi	TYS, ksi	Temp., F
180	174	RT

Specimen Details: Edge Notched
2.25 inches gross width
1.50 inches net width
0.3175 inch notch radius

Surface Condition: Electropolished

Reference: 3.2.3.1.8(f)

Test Parameters:

Loading – Axial
Frequency – 21–1800 cpm
Temperature – RT
Environment – Air

No. of Heats/Lots: Not specified

Equivalent Stress Equation:

Log N_f = 8.87–2.81 log (S_{eq}–41.5)
$S_{eq} = S_{max} (1-R)^{0.46}$
Standard Error of Estimate = 0.18
Standard Deviation in Life = 0.77
R^2 = 94%

Sample Size = 19

[Caution: The equivalent stress model may provide unrealistic life predictions for stress ratios beyond those represented above]

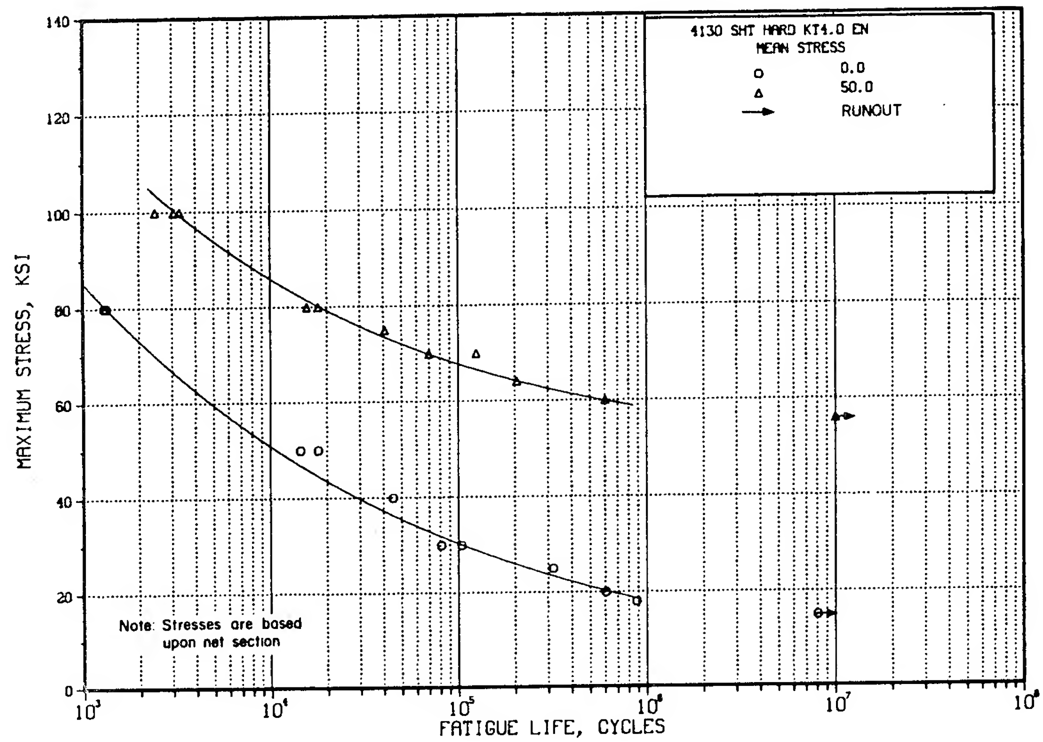


FIGURE 2.3.1.2.8(h). *Best-fit S/N curves for notched, K_t = 4.0, 4130 alloy steel sheet, F_{tu} = 180 ksi, longitudinal direction.*

Correlative Information for Figure 2.3.1.2.8(h)

Product Form: Sheet, 0.075-inch thick

Properties:	TUS, ksi	TYS, ksi	Temp., F
	180	174	RT

Specimen Details: Edge Notched
2.25 inches gross width
1.50 inches net width
0.057 inch notch radius

Surface Condition: Electropolished

Reference: 3.2.3.1.8(f)

Test Parameters:

Loading - Axial
Frequency - 23–1800 cpm
Temperature - RT
Environment - Air

No. of Heats/Lots: Not specified

Equivalent Stress Equation:

Log N_f = 12.4–4.45 log (S_{eq})
$S_{eq} = S_{max} (1-R)^{0.60}$
Standard Error of Estimate = 0.11
Standard Deviation in Life = 0.90
R^2 = 98%

Sample Size = 20

[Caution: The equivalent stress model may provide unrealistic life predictions for stress ratios beyond those represented above]

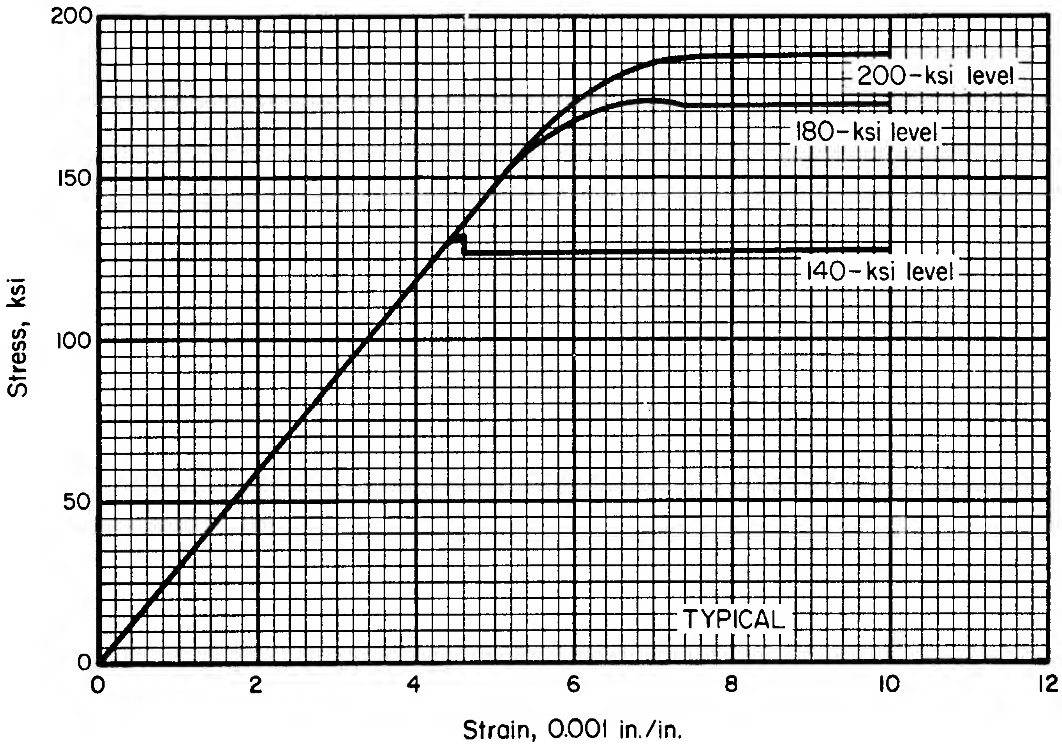


FIGURE 2.3.1.3.6(a). *Typical tensile stress-strain curves at room temperature for heat-treated AISI 4340 alloy steel (all products).*

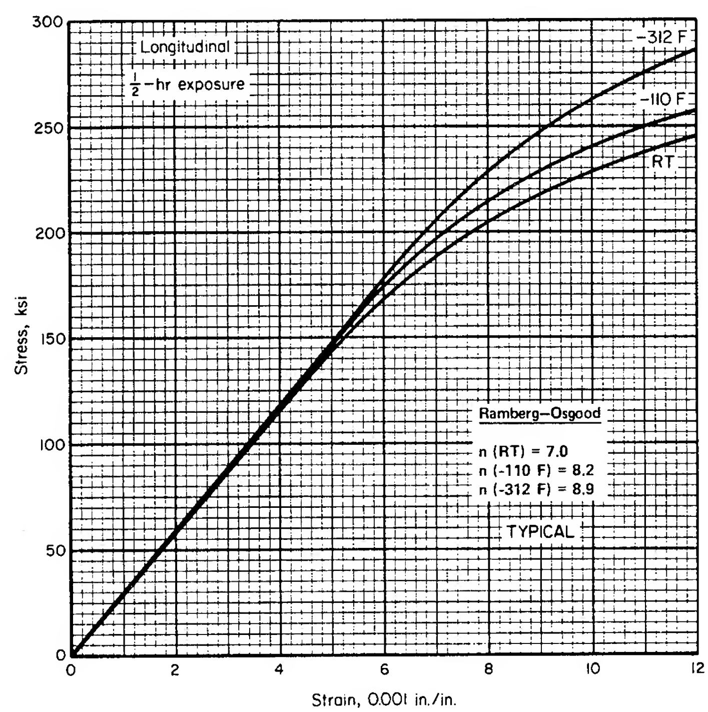


FIGURE 2.3.1.3.6(b). *Typical tensile stress-strain curves at cryogenic and room temperature for AISI 4340 alloy steel bar, F_{tu} = 260 ksi.*

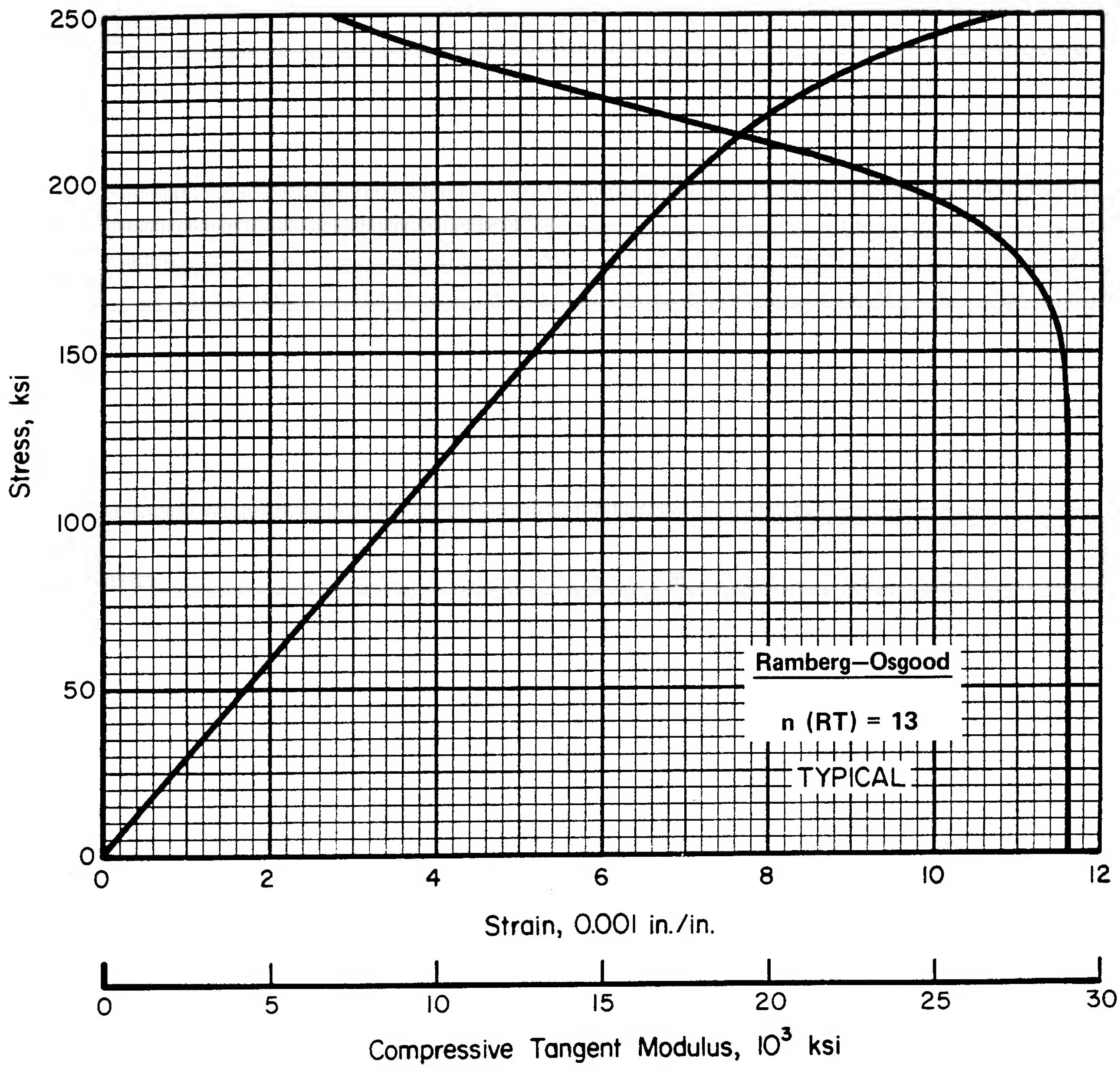


FIGURE 2.3.1.3.6(c). *Typical compressive stress-strain and compressive tangent-modulus curves at room temperature for AISI 4340 alloy steel bar,* F_{tu} *= 260 ksi.*

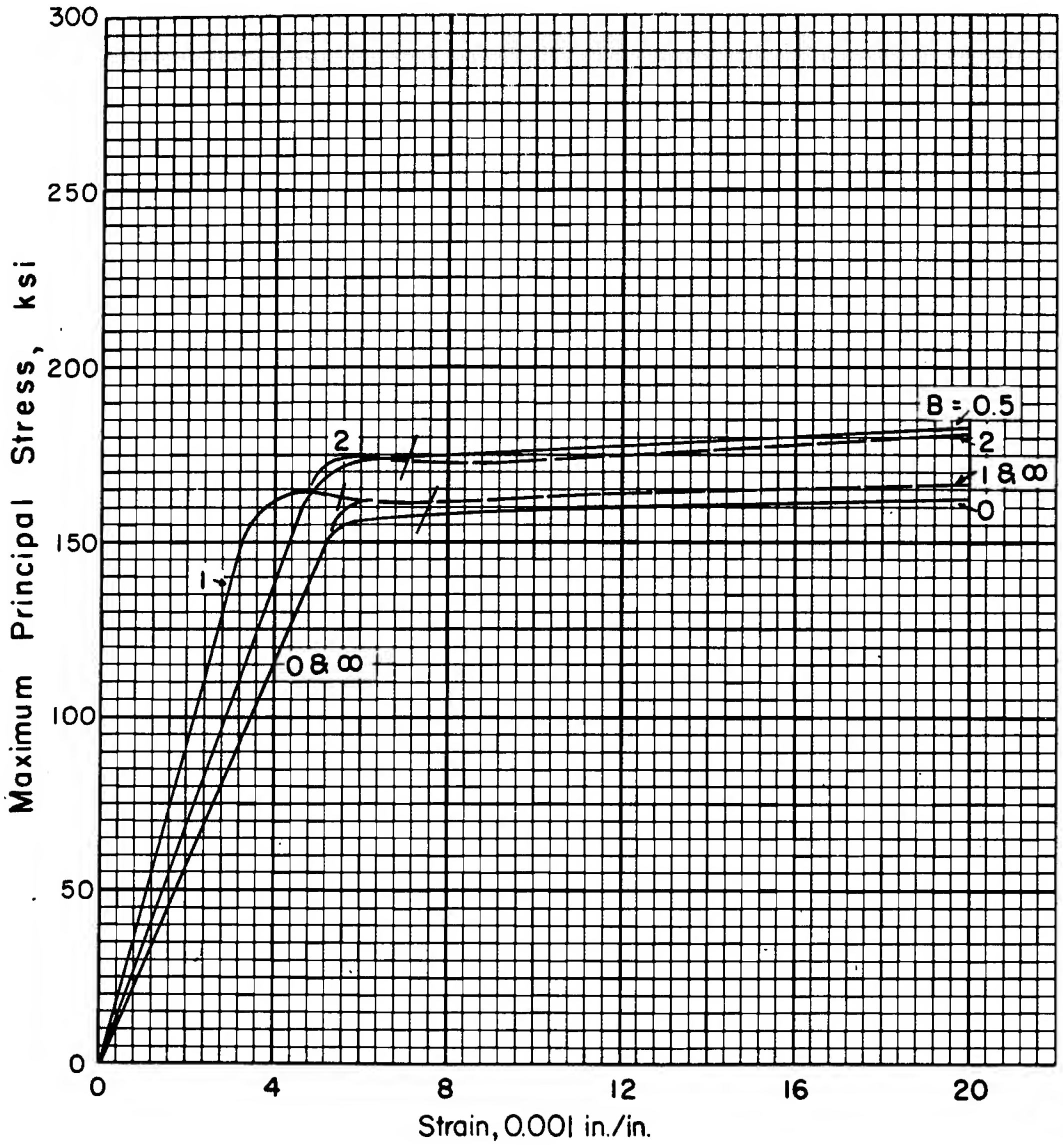


FIGURE 2.3.1.3.6(d). *Typical biaxial stress-strain curves at room temperature for AISI 4340 alloy steel (machined thin-wall cylinders, axial direction = longitudinal direction of bar stock),* F_{tu} *= 180 ksi. A biaxial ratio B of zero corresponds to the hoop direction.*

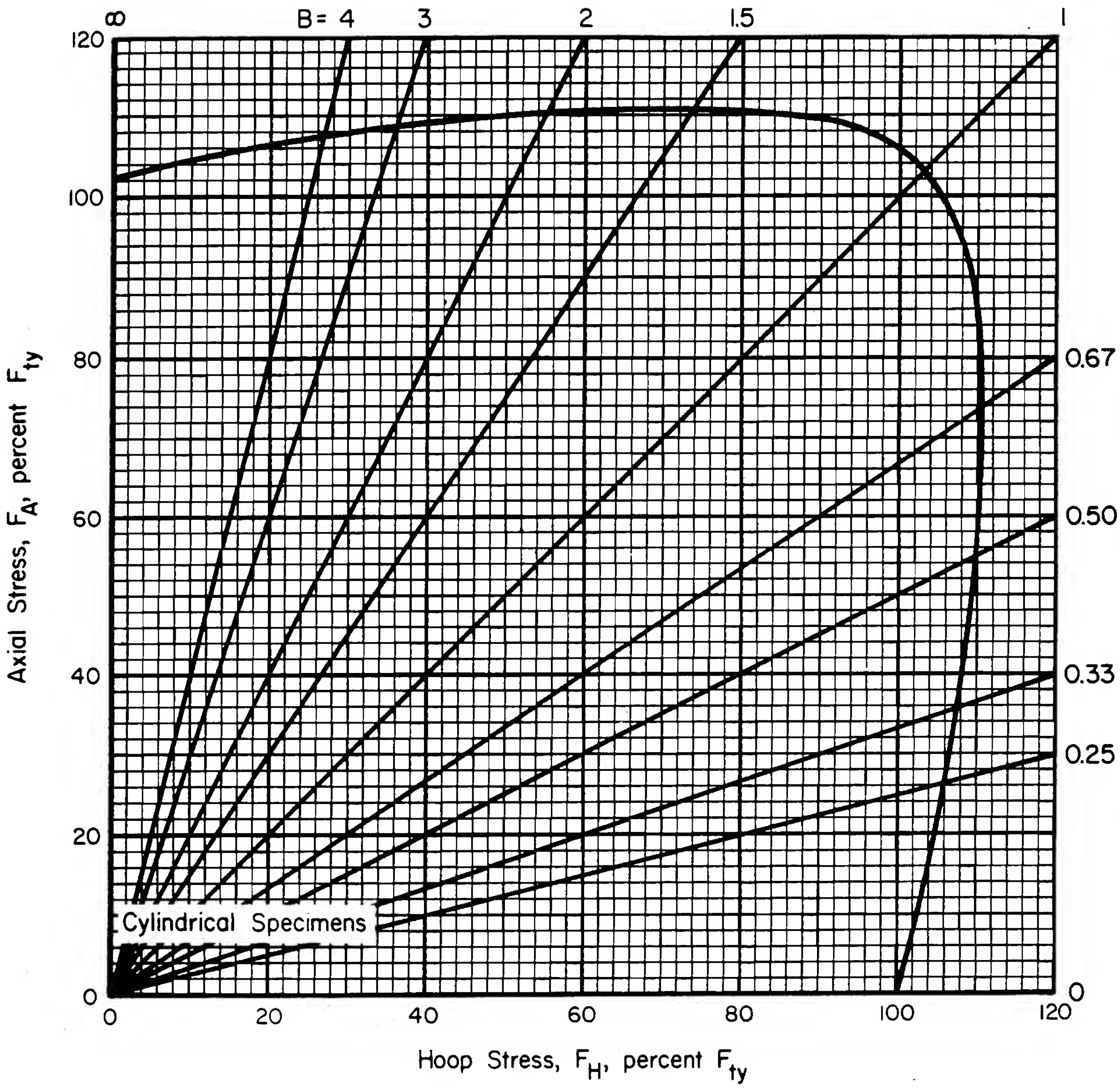


FIGURE 2.3.1.3.6(e). *Biaxial yield-stress envelope at room temperature for AISI 4340 alloy steel (machined thin-wall cylinders, axial direction = longitudinal direction of bar stock), F_{tu} = 180 ksi; F_{ty} measured in the hoop direction.*

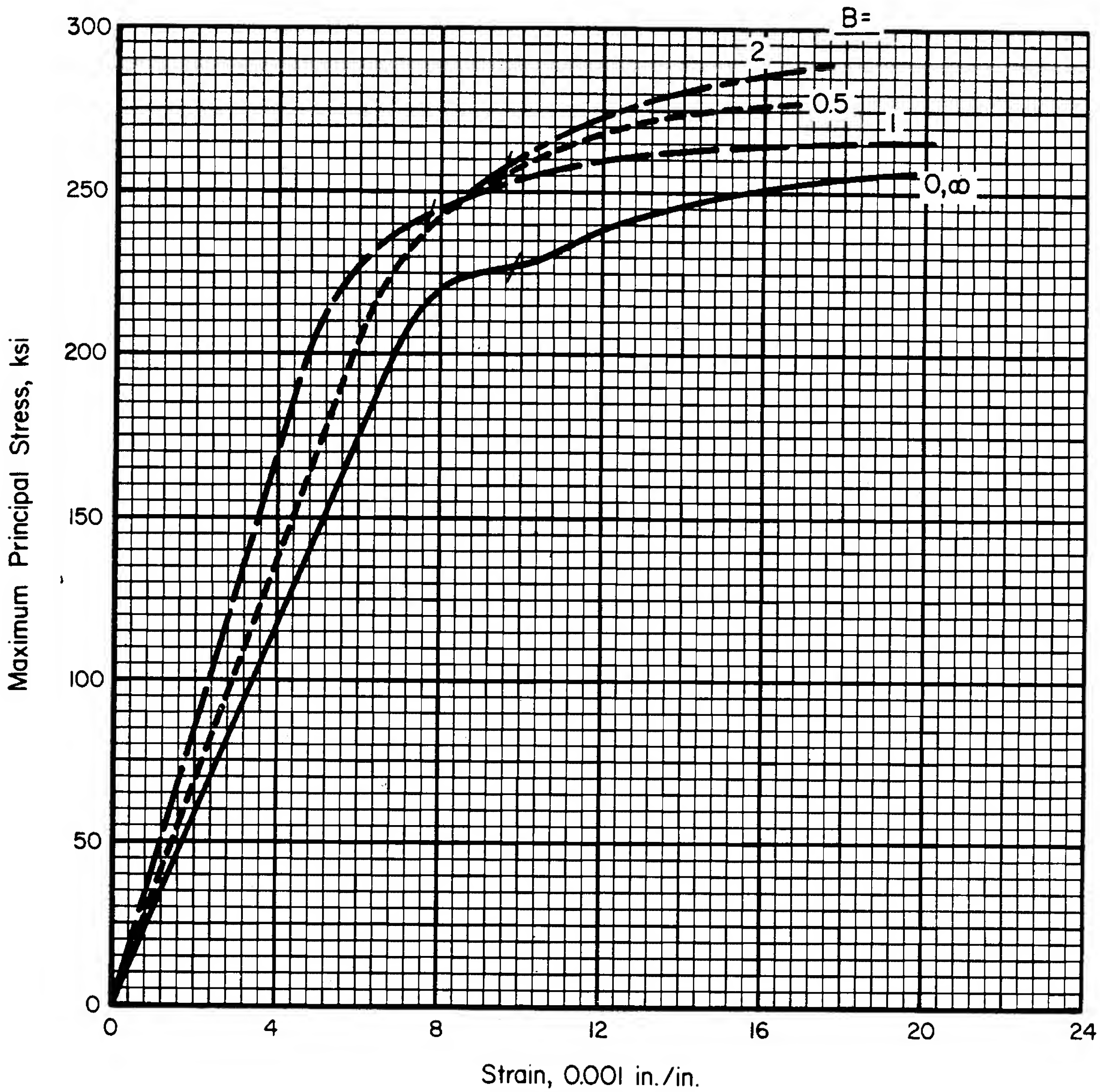


FIGURE 2.3.1.3.6(f). *Typical biaxial stress-strain curves at room temperature for AISI 4340 alloy steel (machined thin-wall cylinders, axial direction = longitudinal direction of bar stock),* F_{tu} *= 260 ksi. A biaxial ratio B of zero corresponds to the hoop direction.*

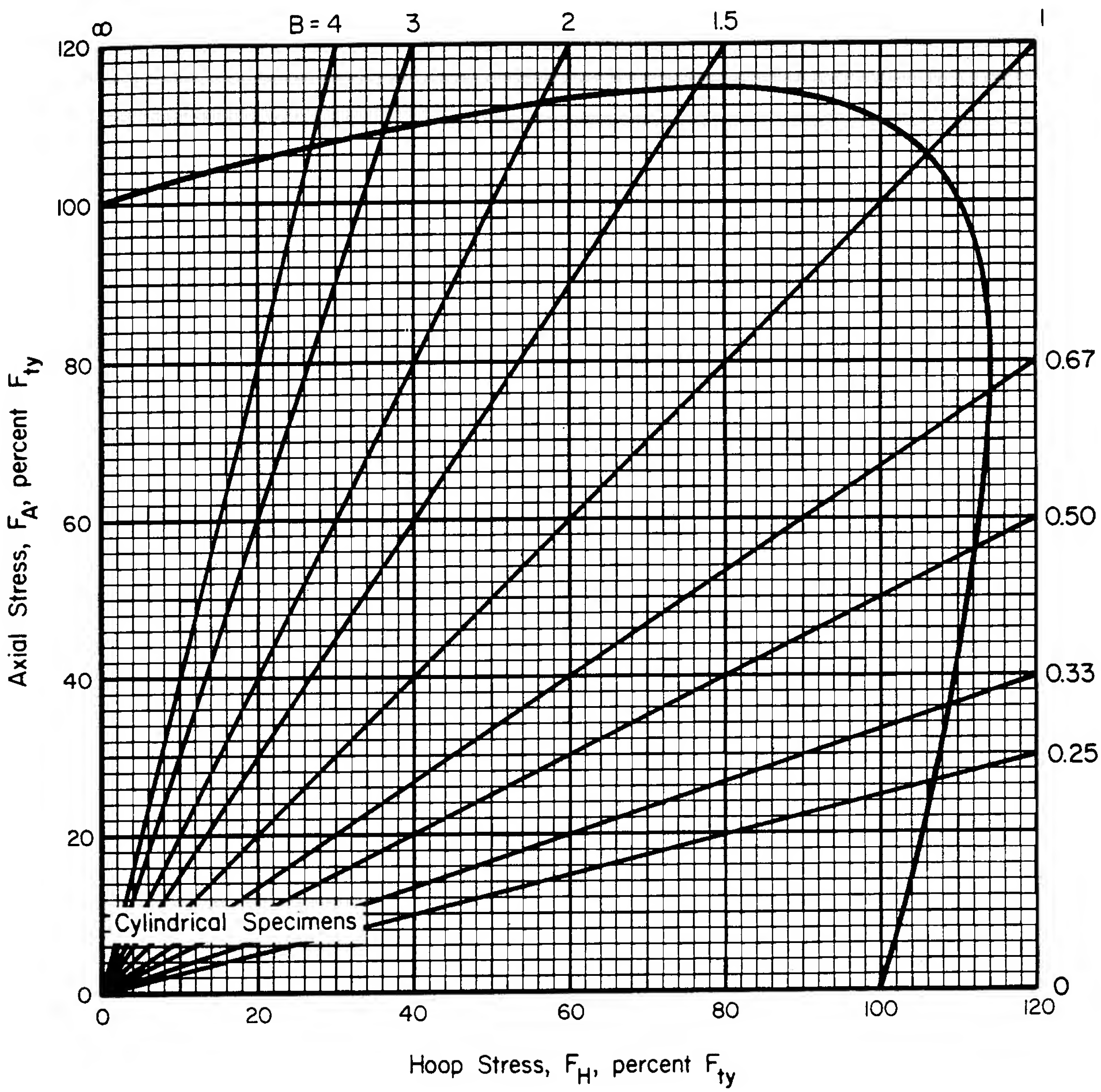


FIGURE 2.3.1.3.6(g). *Biaxial yield-stress envelope at room temperature for AISI 4340 alloy steel (machined thin-wall cylinders, axial direction = longitudinal direction of bar stock), F_{tu} = 260 ksi; F_{ty} measured in the hoop direction.*

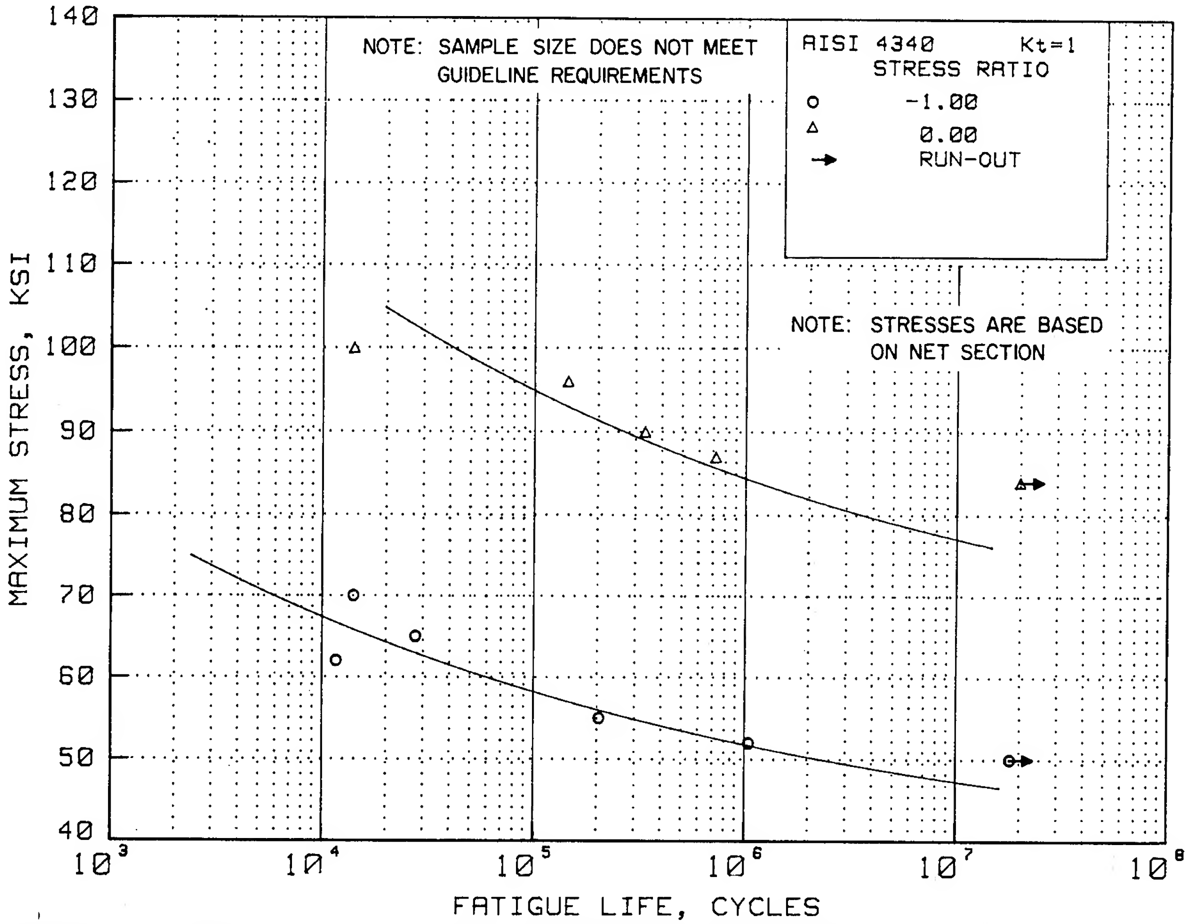


FIGURE 2.3.1.3.8(a). *Best-fit S/N curves for unnotched AISI 4340 alloy steel bar, F_{tu} = 125 ksi, longitudinal direction.*

Correlative Information for Figure 2.3.1.3.8(a)

Product Form: Rolled bar, 1-1/8 inches diameter, air melted

Properties:

TUS, ksi	TYS, ksi	Temp., F
125	—	RT (unnotched)
150	—	RT (notched)

Specimen Details: Unnotched 0.400-inch diameter

Surface Condition: Hand polished to RMS 10

Reference: 2.3.1.3.8(a)

Test Parameters:

Loading - Axial
Frequency - 2000 to 2500 cpm
Temperature - RT
Atmosphere - Air

No. of Heats/Lots: 1

Equivalent Stress Equation:

Log N_f = 14.96–6.46 log (S_{eq} - 60)
$S_{eq} = S_{max} (1-R)^{0.70}$
Standard Error of Estimate = 0.35
Standard Deviation in Life = 0.77
R^2 = 75%

Sample Size = 9

[Caution: The equivalent stress model may provide unrealistic life predictions for stress ratios beyond those represented above]

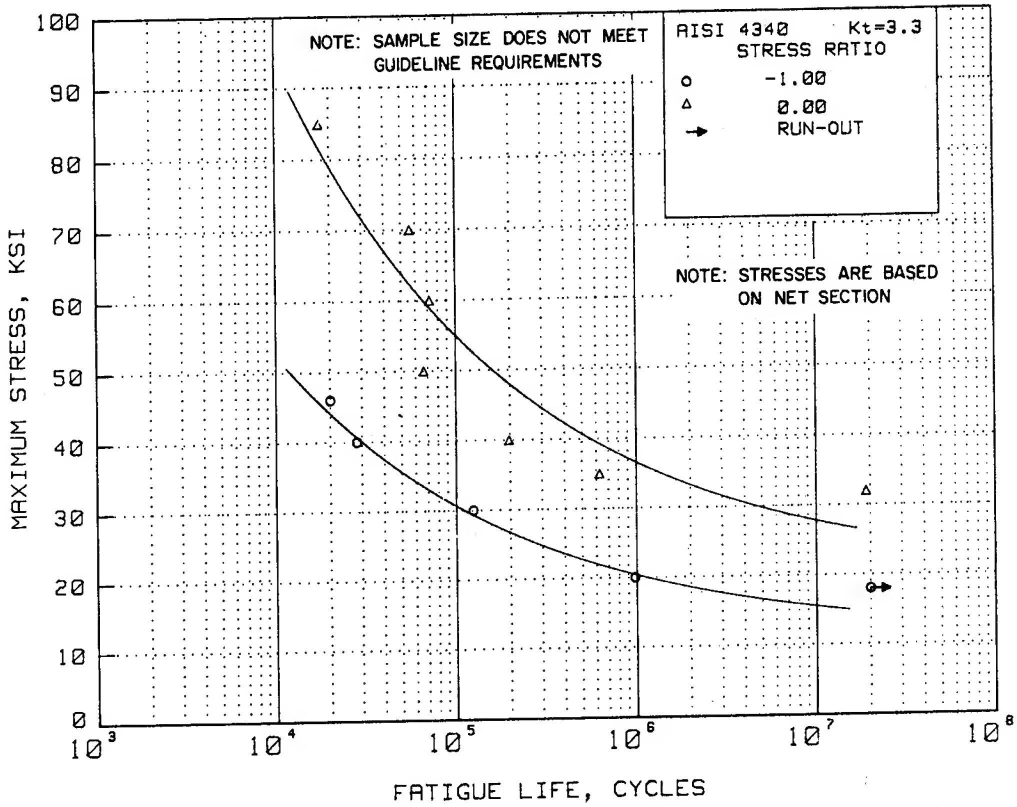


FIGURE 2.3.1.3.8(b). *Best-fit S/N curves for notched, $K_t = 3.3$, AISI 4340 alloy steel bar, $F_{tu} = 125$ ksi, longitudinal direction.*

Correlative Information for Figure 2.3.1.3.8(b)

Product Form: Rolled bar, 1-1/8 inches diameter, air melted

Properties:	TUS, ksi	TYS, ksi	Temp., F
	125	—	RT (unnotched)
	150	—	RT (notched)

Specimen Details: Notched, V-Groove, $K_t = 3.3$
0.450-inch gross diameter
0.400-inch net diameter
0.010-inch root radius, r
60° flank angle, ω

Surface Condition: Lathe turned to RMS 10

Reference: 2.3.1.3.8(a)

Test Parameters:

Loading – Axial
Frequency – 2000 to 2500 cpm
Temperature – RT
Atmosphere – Air

No. of Heats/Lots: 1

Equivalent Stress Equation:

Log N_f = 9.75–3.08 log (S_{eq} - 20.0)
$S_{eq} = S_{max} (1-R)^{0.84}$
Standard Error of Estimate = 0.40
Standard Deviation in Life = 0.90
R^2 = 80%

Sample Size = 11

[Caution: The equivalent stress model may provide unrealistic life predictions for stress ratios beyond those represented above]

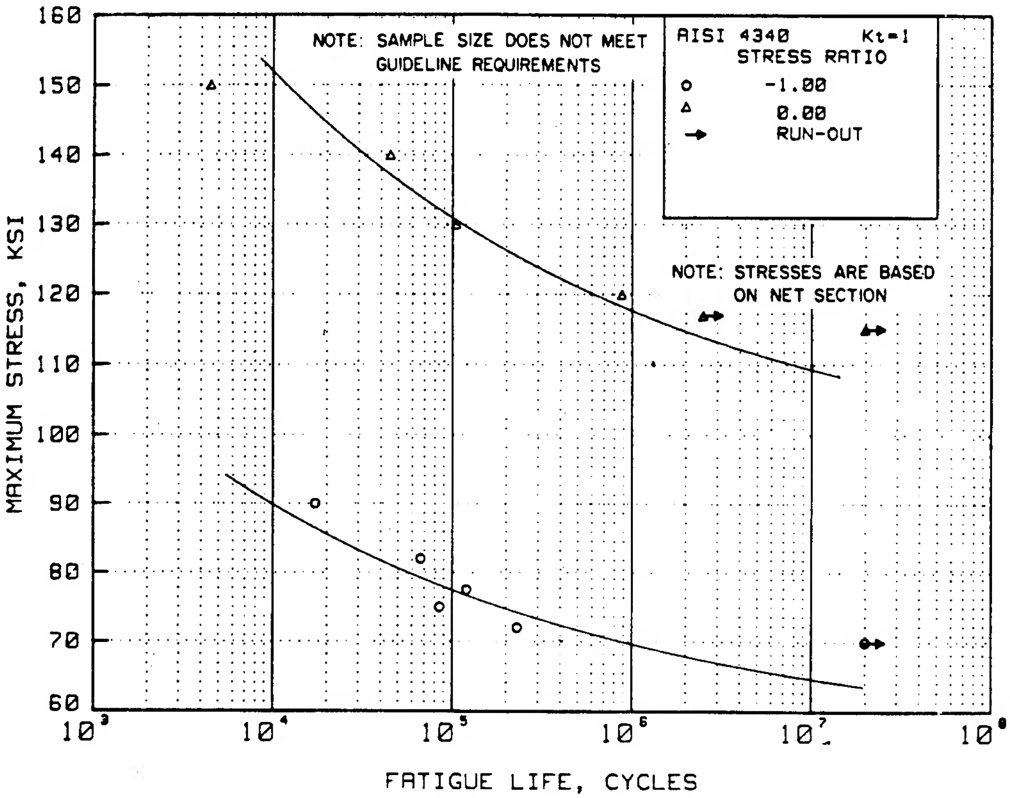


FIGURE 2.3.1.3.8(c). *Best-fit S/N curves for unnotched AISI 4340 alloy steel bar, F_{tu} = 150 ksi, longitudinal direction.*

Correlative Information for Figure 2.3.1.3.8(c)

Product Form: Rolled bar, 1.125 inches diameter, air melted

Properties:

TUS, ksi	TYS, ksi	Temp., F
158	147	RT (unnotched)
190	—	RT (notched)

Specimen Details: Unnotched
0.400-inch diameter

Surface Condition: Hand polished to RMS 10

Reference: 2.3.1.3.8(b)

Test Parameters:
Loading - Axial
Frequency - 2000 to 2500 cpm
Temperature - RT
Atmosphere - Air

No. of Heat/Lots: 1

Equivalent Stress Equation:
Log N_f = 10.76-3.91 log (S_{eq} - 101.0)
$S_{eq} = S_{max}$ $(1-R)^{0.77}$
Standard Deviation of Log (Life) = 0.33
Adjusted R^2 Statistic = 73%

Sample Size = 9

[Caution: The equivalent stress model may provide unrealistic life predictions for stress ratios beyond those represented above.]

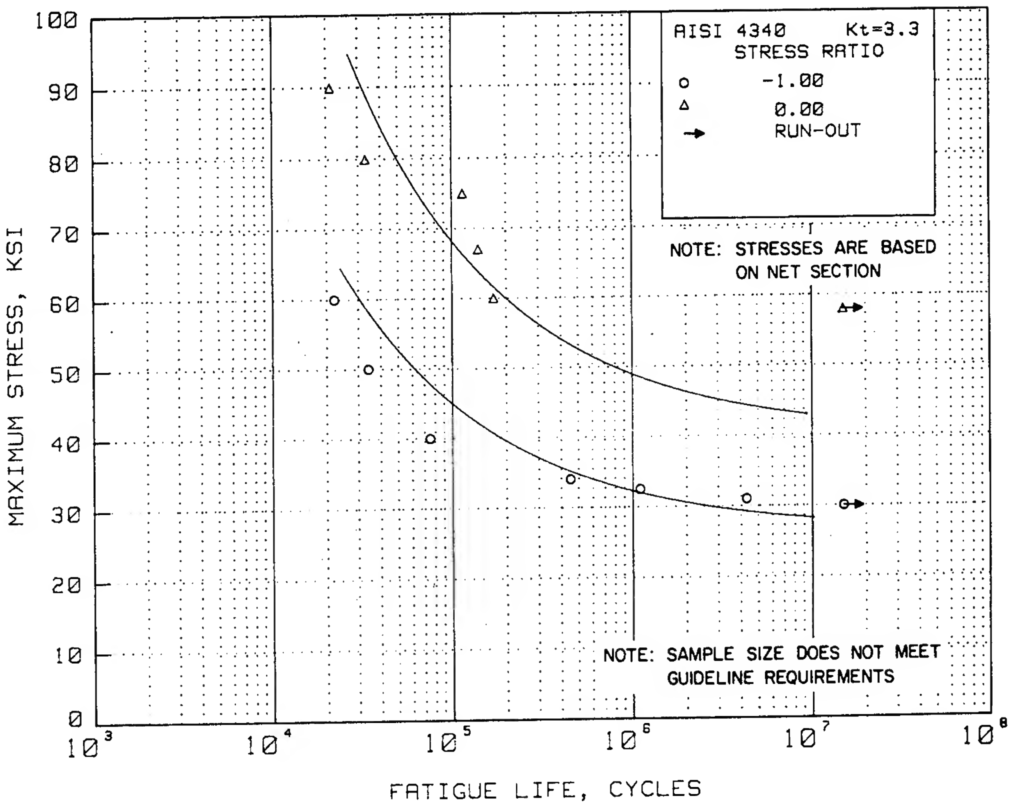


FIGURE 2.3.1.3.8(d). *Best-fit S/N curves for notched, K_t = 3.3, AISI 4340 alloy steel bar, F_{tu} = 150 ksi, longitudinal direction.*

Correlative Information for Figure 2.3.1.3.8(d)

Product Form: Rolled bar, 1-1/8 inches diameter, air melted

Properties:	TUS, ksi	TYS, ksi	Temp., F
	158	147	RT (unnotched)
	190	—	RT (notched)

Specimen Details: Notched, V-Groove, K_t = 3.3
0.450-inch gross diameter
0.400-inch net diameter
0.010-inch root radius, r
60° flank angle, ω

Surface Condition: Lathe turned to RMS 10

Reference: 2.3.1.3.8(a)

Test Parameters:

Loading – Axial
Frequency – 2000 to 2500 cpm
Temperature – RT
Atmosphere – Air

No. of Heats/Lots: 1

Equivalent Stress Equation:

$\text{Log } N_f = 7.90 - 2.00 \log (S_{eq} - 40.0)$

$S_{eq} = S_{max} (1-R)^{0.60}$
Standard Error of Estimate = 0.27
Standard Deviation in Life = 0.74
R^2 = 86%

Sample Size = 11

[Caution: The equivalent stress model may provide unrealistic life predictions for stress ratios beyond those represented above]

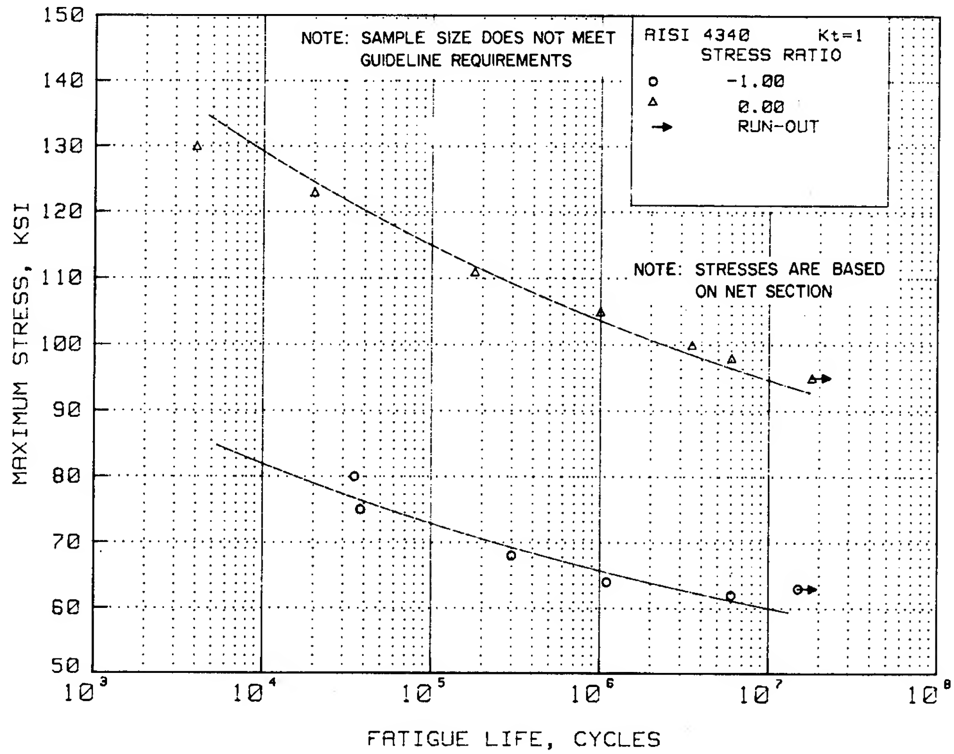


FIGURE 2.3.1.3.8(e). *Best-fit S/N curves for unnotched AISI 4340 alloy steel bar at 600 F, F_{tu} = 150 ksi, longitudinal direction.*

Correlative Information for Figure 2.3.1.3.8(e)

Product Form: Rolled bar, 1-1/8 inches diameter, air melted

Properties:

TUS, ksi	TYS, ksi	Temp., F
158	147	RT (unnotched)
153	121	600 (unnotched)
190	—	RT (notched)
176	—	600 (notched)

Specimen Details: Unnotched
0.400-inch diameter

Surface Condition: Hand polished to RMS 10

Reference: 2.3.1.3.8(b)

Test Parameters:

Loading – Axial
Frequency – 2000 to 2500 cpm
Temperature – 600 F
Atmosphere – Air

No. of Heats/Lots: 1

Equivalent Stress Equation:

Log N_f = 22.36–9.98 log (S_{eq} - 60.0)
$S_{eq} = S_{max} (1\text{-}R)^{0.66}$
Standard Error of Estimate = 0.24
Standard Deviation in Life = 1.08
R^2 = 95%

Sample Size = 11

[Caution: The equivalent stress model may provide unrealistic life predictions for stress ratios beyond those represented above]

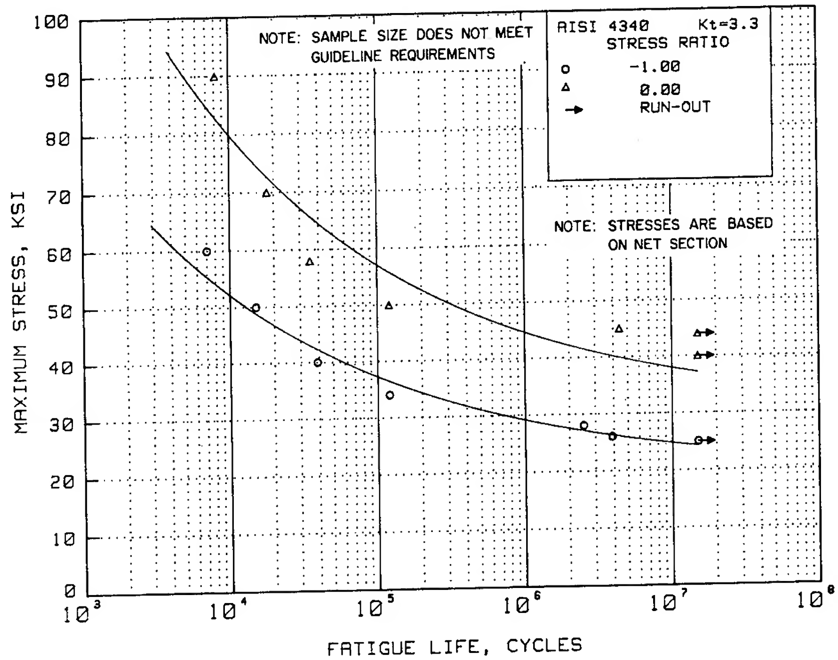


FIGURE 2.3.1.3.8(f). *Best-fit S/N curves for notched, K_t = 3.3, AISI 4340 alloy steel bar at 600 F, F_{tu} = 150 ksi, longitudinal direction.*

Correlative Information for Figure 2.3.1.3.8(f)

Product Form: Rolled bar, 1-1/8 inches diameter, air melted

Properties:

TUS, ksi	TYS, ksi	Temp., F
158	147	RT (unnotched)
153	121	600 (unnotched)
190	—	RT (notched)
176	—	600 (notched)

Specimen Details: Notched, V-Groove, K_t = 3.3
0.450-inch gross diameter
0.400-inch net diameter
0.010-inch root radius, r
60° flank angle, ω

Surface Condition: Lathe turned to RMS 10

Reference: 2.3.1.3.8(b)

Test Parameters:

Loading – Axial
Frequency – 2000 to 2500 cpm
Temperature – 600 F
Atmosphere – Air

No. of Heats/Lots: 1

Equivalent Stress Equation:

$\text{Log } N_f = 10.39 - 3.76 \log (S_{eq} - 30.0)$
$S_{eq} = S_{max} (1-R)^{0.62}$
Standard Error of Estimate = 0.36
Standard Deviation in Life = 1.06
R^2 = 89%

Sample Size = 11

[Caution: The equivalent stress model may provide unrealistic life predictions for stress ratios beyond those represented above]

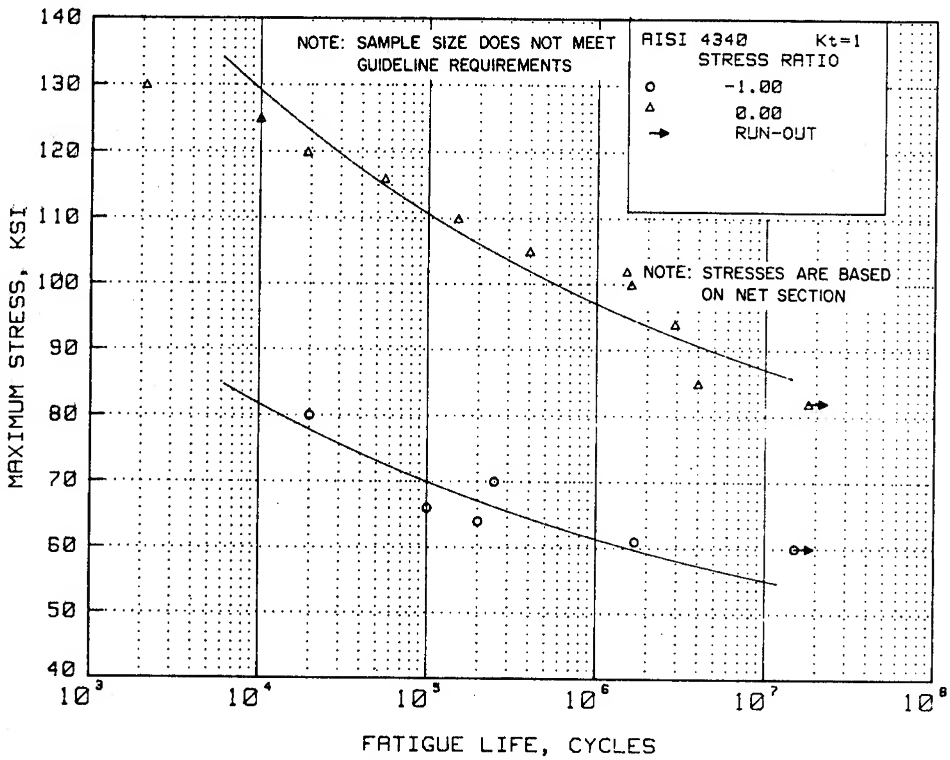


FIGURE 2.3.1.3.8(g). *Best-fit S/N curves for unnotched AISI 4340 alloy steel bar at 800 F, F_{tu} = 150 ksi, longitudinal direction.*

Correlative Information for Figure 2.3.1.3.8(g)

Product Form: Rolled bar, 1-1/8 inches diameter, air melted

Properties:

TUS, ksi	TYS, ksi	Temp., F
158	147	RT (unnotched)
125	101	800 (unnotched)
190	—	RT (notched)
154	—	800 (notched)

Specimen Details: Unnotched
0.400-inch diameter

Surface Condition: Hand polished to RMS 10

Reference: 2.3.1.3.8(b)

Test Parameters:

Loading - Axial
Frequency - 2000 to 2500 cpm
Temperature - 800 F
Atmosphere - Air

No. of Heats/Lots: 1

Equivalent Stress Equation:

Log N_f = 17.53–7.35 log (S_{eq} - 60.0)
$S_{eq} = S_{max} (1-R)^{0.66}$
Standard Error of Estimate = 0.42
Standard Deviation in Life = 0.99
R^2 = 82%

Sample Size = 15

[Caution: The equivalent stress model may provide unrealistic life predictions for stress ratios beyond those represented above]

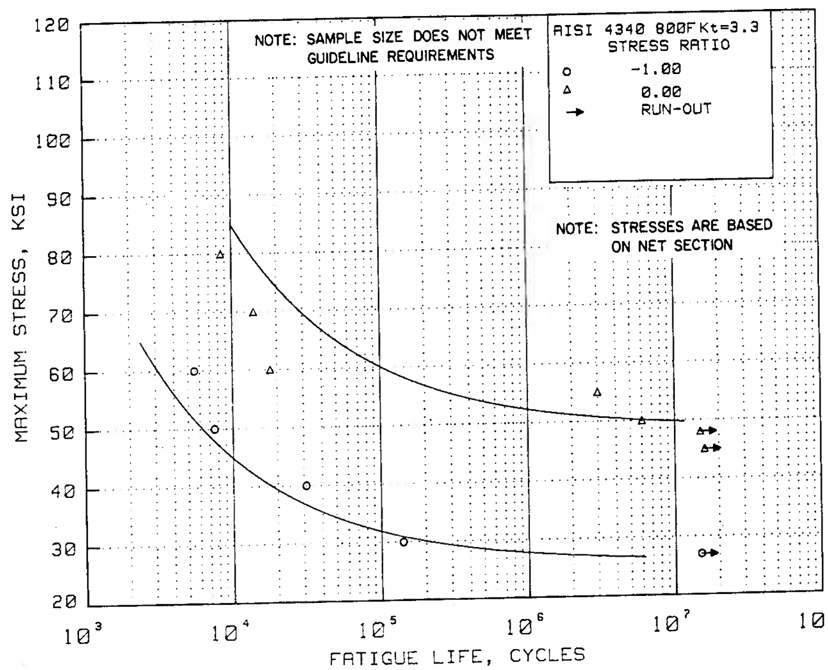


FIGURE 2.3.1.3.8(h). *Best-fit S/N curves for notched, K_t = 3.3 AISI 4340 alloy steel bar at 800 F, F_{tu} = 150 ksi, longitudinal direction.*

Correlative Information for Figure 2.3.1.3.8(h)

Product Form: Rolled bar, 1-1/8 inches diameter, air melted

Properties:	TUS, ksi	TYS, ksi	Temp., F
	158	147	RT (unnotched)
	125	101	800 (unnotched)
	190	—	RT (notched)
	154	—	800 (notched)

Specimen Details: Notched, V-Groove, K_t = 3.3
0.450-inch gross diameter
0.400-inch net diameter
0.010-inch root radius, r
60° flank angle, ω

Surface Condition: Lathe turned to RMS 10

Reference: 2.3.1.3.8(b)

Test Parameters:

Loading – Axial
Frequency – 2000 to 2500 cpm
Temperature – 800 F
Atmosphere – Air

No. of Heats/Lots: 1

Equivalent Stress Equation:

Log N_f = 7.31–2.01 log (S_{eq} - 48.6)
$S_{eq} = S_{max}\ (1\text{-}R)^{0.92}$
Standard Error of Estimate = 0.60
Standard Deviation in Life = 1.14
R^2 = 72%

Sample Size = 9

[Caution: The equivalent stress model may provide unrealistic life predictions for stress ratios beyond those represented above]

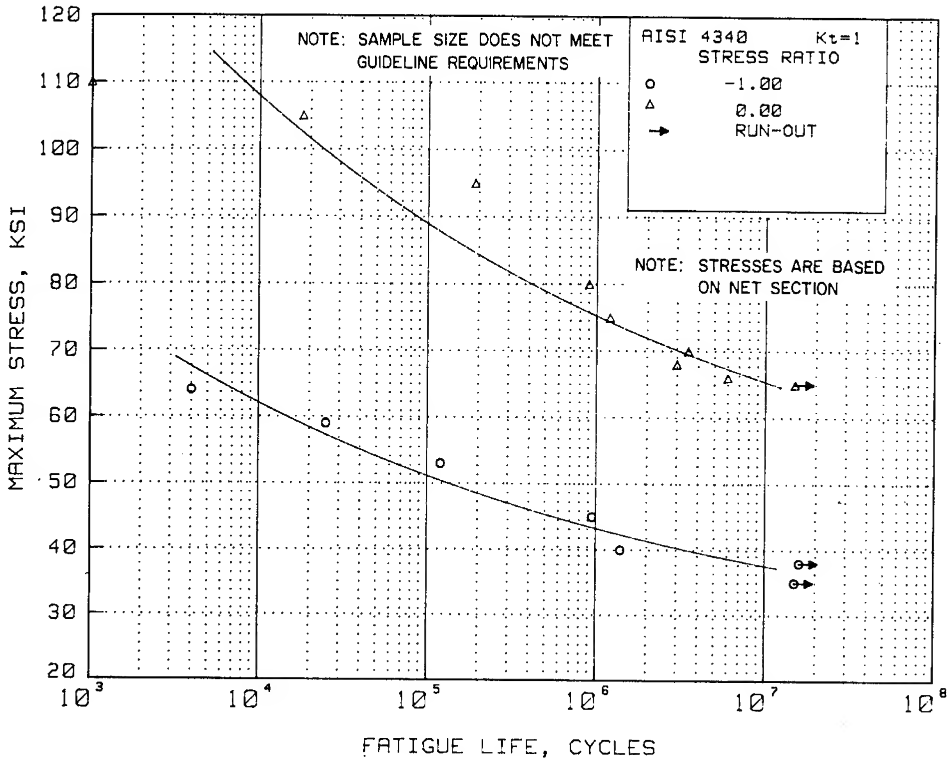


FIGURE 2.3.1.3.8(i). *Best-fit S/N curves for unnotched AISI 4340 alloy steel bar at 1000 F, F_{tu} = 150 ksi, longitudinal direction.*

Correlative Information for Figure 2.3.1.3.8(i)

Product Form: Rolled bar, 1-1/8 inches diameter, air melted

Properties:	TUS, ksi	TYS, ksi	Temp., F
	158	147	RT (unnotched)
	81	63	1000 F (unnotched)
	190	—	RT (notched)
	98	—	1000 F (notched)

Specimen Details: Unnotched
0.400-inch diameter

Surface Condition: Hand polished to RMS 10

Reference: 2.3.1.3.8(b)

Test Parameters:

Loading - Axial
Frequency - 2000 to 2500 cpm
Temperature - 1000 F
Atmosphere - Air

No. of Heats/Lots: 1

Equivalent Stress Equation:

Log N_f = 16.85–7.02 log (S_{eq} - 40.0)
$S_{eq} = S_{max} (1-R)^{0.80}$
Standard Error of Estimate = 0.42
Standard Deviation in Life = 1.20
R^2 = 88%

Sample Size = 13

[Caution: The equivalent stress model may provide unrealistic life predictions for stress ratios beyond those represented above]

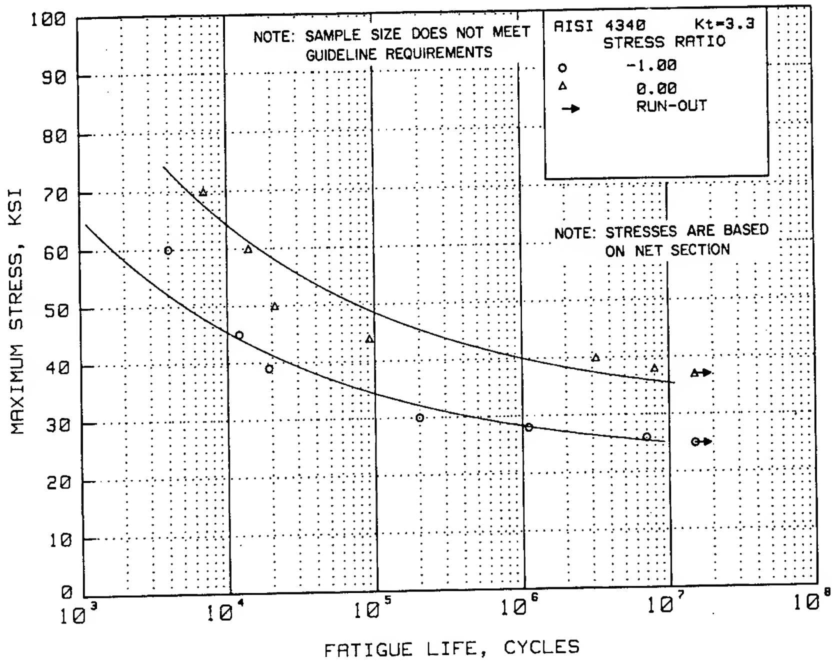


FIGURE 2.3.1.3.8(j). *Best-fit S/N curves for notched,* K_t = 3.3, *AISI 4340 alloy steel bar at 1000 F,* F_{tu} *= 150 ksi, longitudinal direction.*

Correlative Information for Figure 2.3.1.3.8(j)

Product Form: Rolled bar, 1-1/8 inches diameter, air melted

Properties:

TUS, ksi	TYS, ksi	Temp., F
158	147	RT (unnotched)
81	63	1000 F (unnotched)
190	—	RT (notched)
98	—	1000 F (notched)

Specimen Details: Notched, V-Groove, K_t = 3.3
0.450-inch gross diameter
0.400-inch net diameter
0.010-inch root radius, r
60° flank angle, ω

Surface Condition: Lathe turned to RMS 10

Reference: 2.3.1.3.8(b)

Test Parameters:

Loading – Axial
Frequency – 2000 to 2500 cpm
Temperature – 1000 F
Atmosphere – Air

No. of Heats/Lots: 1

Equivalent Stress Equation:

$\log N_f = 9.76 - 3.75 \log (S_{eq} - 30.0)$
$S_{eq} = S_{max} (1-R)^{0.50}$
Standard Error of Estimate = 0.40
Standard Deviation in Life = 1.22
R^2 = 89%

Sample Size = 12

[Caution: The equivalent stress model may provide unrealistic life predictions for stress ratios beyond those represented above]

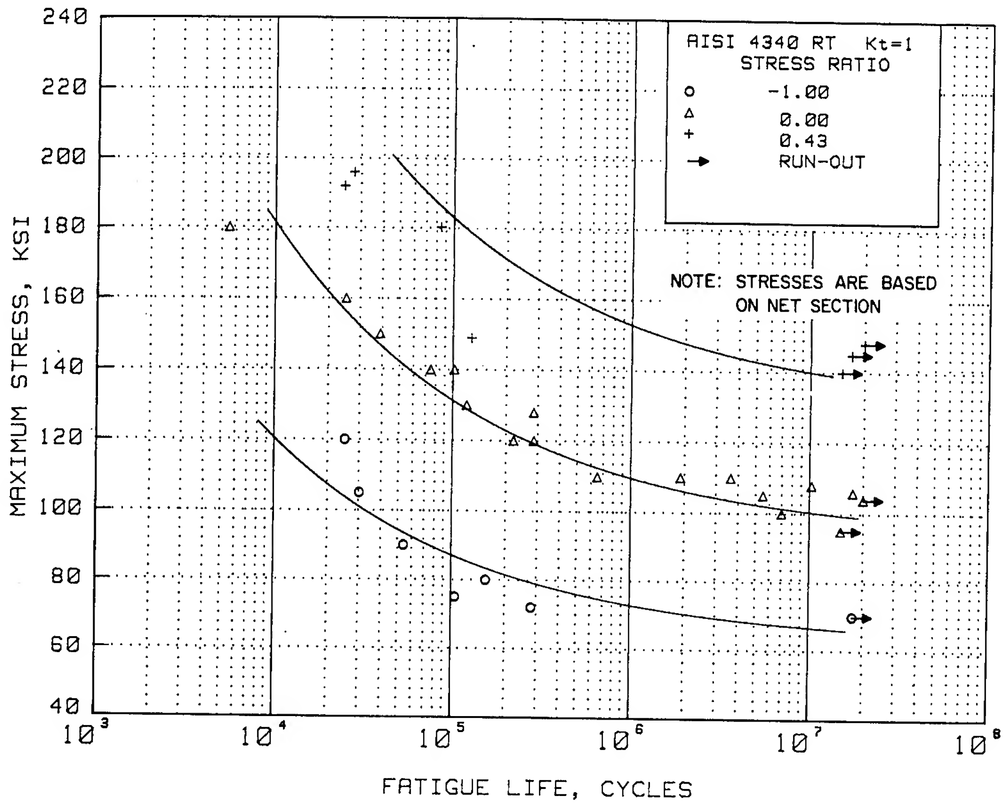


FIGURE 2.3.1.3.8(k). *Best-fit S/N curves for unnotched AISI 4340 alloy steel bar and die forging, F_{tu} = 200 ksi, longitudinal direction.*

Correlative Information for Figure 2.3.1.3.8(k)

Product Forms: Rolled bar, 1-1/8 inches diameter, air melted
Die forging (landing gear-B36 aircraft), air melted

Properties:

TUS, ksi	TYS, ksi	Temp., F
208, 221	189, 217	RT (unnotched)
251	—	RT (notched)

Specimen Details: Unnotched
0.300 and 0.400-inch diameter

Surface Condition: Hand polished to RMS 5–10

Reference: 2.3.1.3.8(a) and (c)

Test Parameters:

Loading – Axial
Frequency – 2000 to 2500 cpm
Temperature – RT
Atmosphere – Air

No. of Heats/Lots: 2

Equivalent Stress Equation:

$\text{Log } N_f = 9.31 - 2.73 \log (S_{eq} - 93.4)$
$S_{eq} = S_{max} (1-R)^{0.59}$
Standard Error of Estimate = 0.49
Standard Deviation in Life = 0.93
R^2 = 72%

Sample Size = 26

[Caution: The equivalent stress model may provide unrealistic life predictions for stress ratios beyond those represented above]

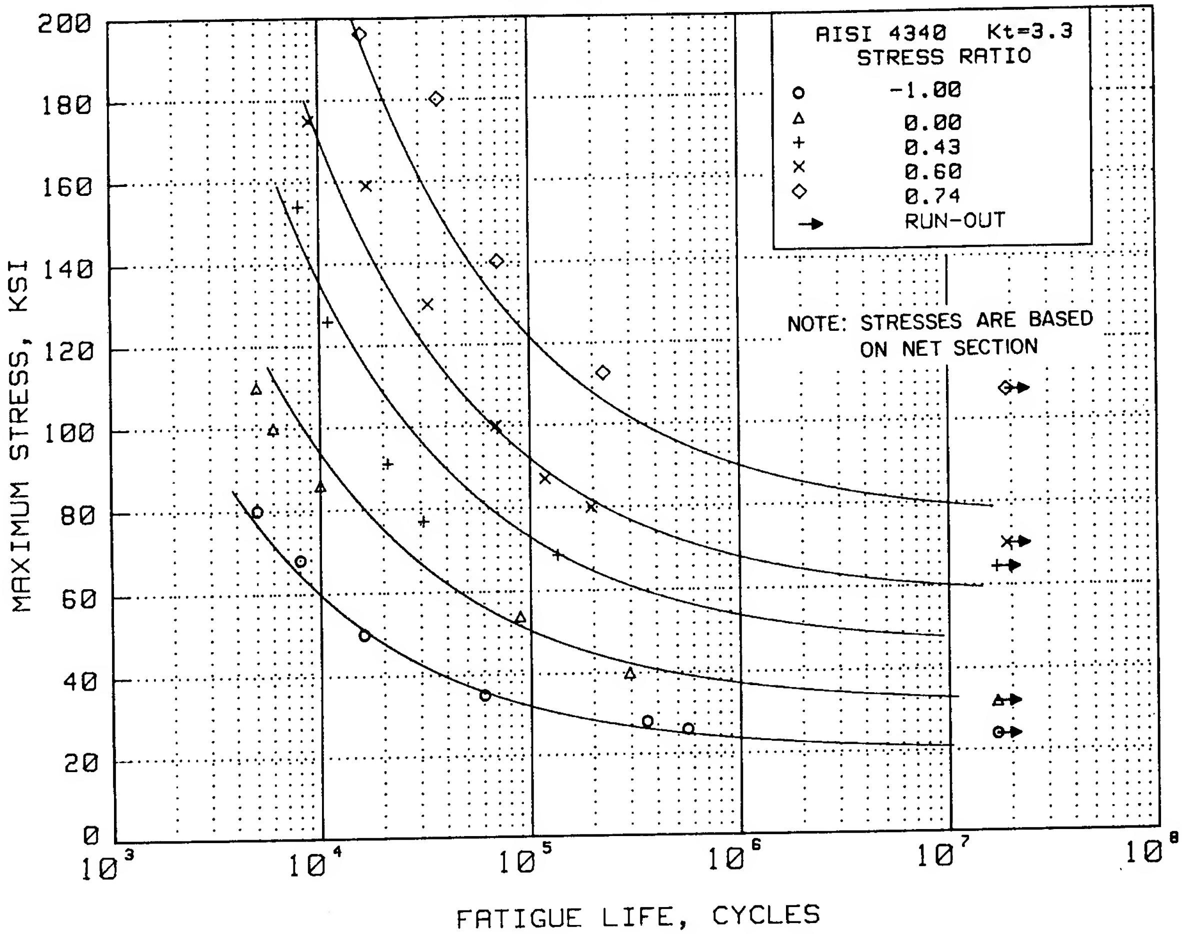


FIGURE 2.3.1.3.8(l). *Best-fit S/N curves for notched, K_t = 3.3, AISI 4340 alloy steel bar, F_{tu} = 200 ksi, longitudinal direction.*

Correlative Information for Figure 2.3.1.3.8(l)

Product Form: Rolled bar, 1-1/8 inches diameter, air melted

Properties:	TUS, ksi	TYS, ksi	Temp., F
	208	—	RT (unnotched)
	251	—	RT (notched)

Specimen Details: Notched, V-Groove, K_t = 3.3
0.450-inch gross diameter
0.400-inch net diameter
0.010-inch root radius, r
60° flank angle, ω

Surface Condition: Lathe turned to RMS 10

Reference: 2.3.1.3.8(a)

Test Parameters:

Loading – Axial
Frequency – 2000 to 2500 cpm
Temperature – RT
Atmosphere – Air

No. of Heats/Lots: 1

Equivalent Stress Equation:

Log N_f = 7.52–1.96 log (S_{eq} - 31.2)
$S_{eq} = S_{max} (1-R)^{0.65}$
Standard Error of Estimate = 0.16
Standard Deviation in Life = 0.62
R^2 = 93%

Sample Size = 26

[Caution: The equivalent stress model may provide unrealistic life predictions for stress ratios beyond those represented above]

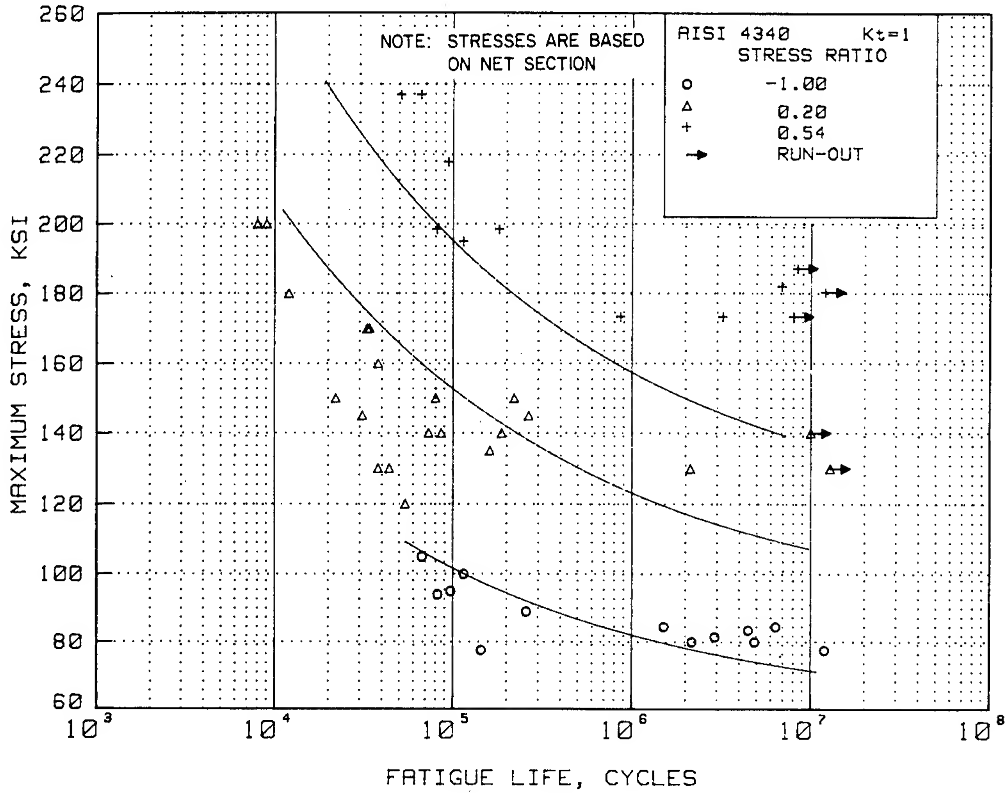


FIGURE 2.3.1.3.8(m). *Best-fit S/N curves for unnotched AISI 4340 alloy steel bar and billet, F_{tu} = 260 ksi, longitudinal direction.*

Correlative Information for Figure 2.3.1.3.8(m)

Product Forms: Rolled bar, 1-1/8 inches diameter, air melted
Billet, 6 inches RCS air melted

Properties:

TUS, ksi	TYS, ksi	Temp., F
266, 291	232	RT (unnotched)
352	—	RT (notched)

Specimen Details: Unnotched
0.200 and 0.400-inch diameter

Surface Condition: Hand polished to RMS 10

References: 2.3.1.3.8(a) and (d)

Test Parameters:

Loading – Axial
Frequency – 1800 to 2500 cpm
Temperature – RT
Atmosphere – Air

No. of Heats/Lots: 2

Equivalent Stress Equation:

$\text{Log } N_f = 11.62 - 3.75 \log (S_{eq} - 80.0)$
$S_{eq} = S_{max} (1-R)^{0.44}$
Standard Error of Estimate = 0.64
Standard Deviation in Life = 0.86
R^2 = 45%

Sample Size = 41

[Caution: The equivalent stress model may provide unrealistic life predictions for stress ratios beyond those represented above]

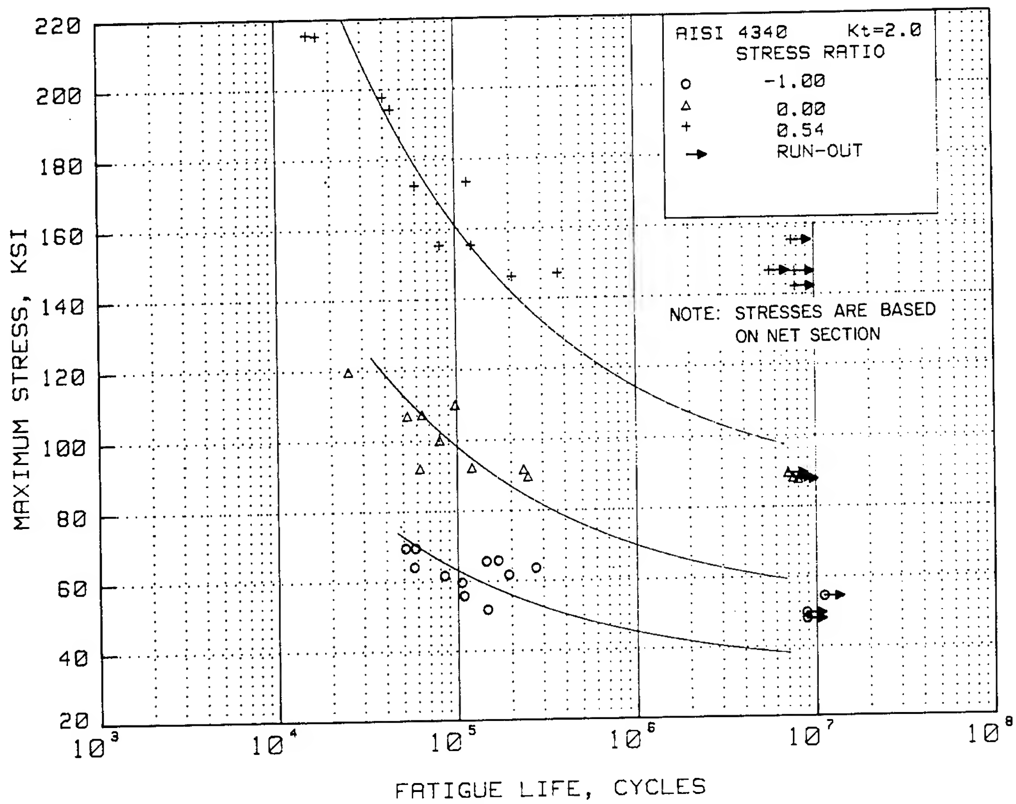


FIGURE 2.3.1.3.8(n). *Best-fit S/N curves for notched, K_t = 2.0, AISI 4340 alloy steel bar, F_{tu} = 260 ksi, longitudinal direction.*

Correlative Information for Figure 2.3.1.3.8(n)

Product Form: Rolled bar, 1-1/8 inches diameter, air melted

Properties:	TUS, ksi	TYS, ksi	Temp., F
	266	232	RT (unnotched)
	390	—	RT (notched)

Specimen Details: Notched, V-Groove, K_t = 2.0
0.300-inch gross diameter
0.220-inch net diameter
0.030-inch root radius, r
60° flank angle, ω

Surface Condition: Lathe turned to RMS 10

Reference: 2.3.1.3.8(a)

Test Parameters:

Loading - Axial
Frequency - 2000 to 2500 cpm
Temperature - RT
Atmosphere - Air

No. of Heats/Lots: 1

Equivalent Stress Equation:

Log N_f = 9.46–2.65 log (S_{eq} - 50.0)
$S_{eq} = S_{max} (1-R)^{0.64}$
Standard Error of Estimate = 0.22
Standard Deviation in Life = 0.34
R^2 = 58%

Sample Size = 30

[Caution: The equivalent stress model may provide unrealistic life predictions for stress ratios beyond those represented above]

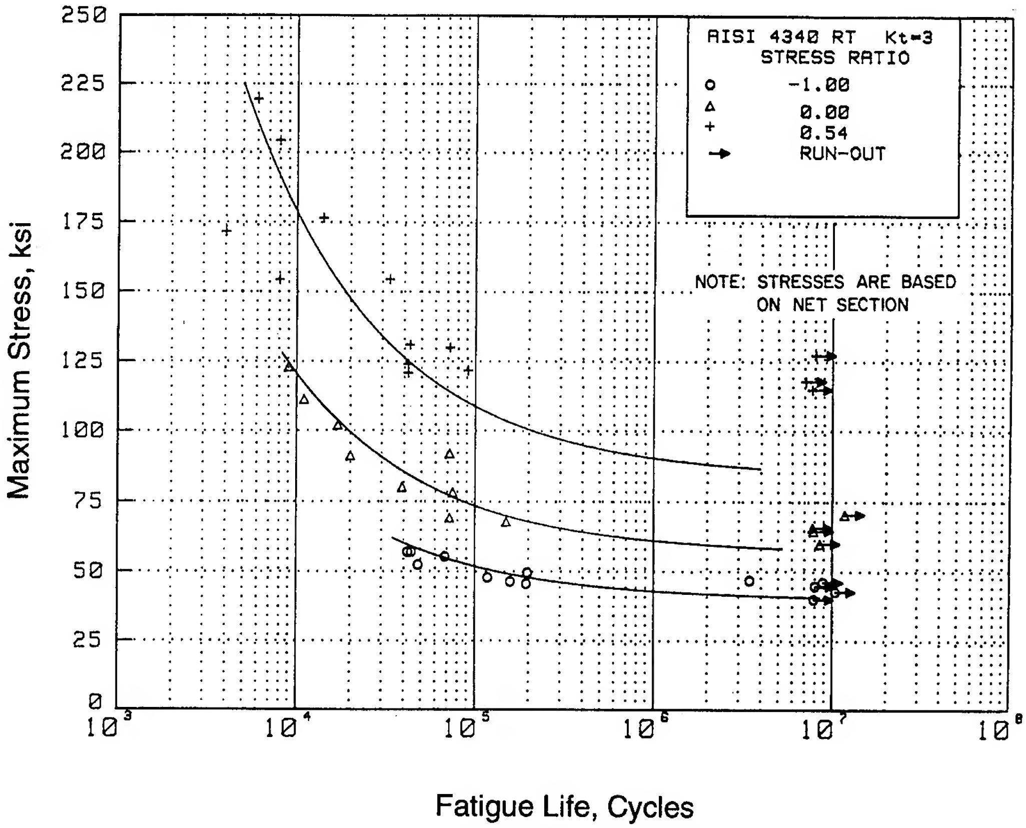


FIGURE 2.3.1.3.8(o). *Best-fit S/N curves for notched, K_t = 3.0, AISI 4340 alloy steel bar, F_{tu} = 260 ksi, longitudinal direction.*

Correlative Information for Figure 2.3.1.3.8(o)

Product Form: Rolled bar, 1-1/8 inches diameter, air melted

Properties:

TUS, ksi	TYS, ksi	Temp., F
266	232	RT (unnotched)
352	—	RT (notched)

Specimen Details: Notched, V-Groove, K_t = 3.0
0.270-inch gross diameter
0.220-inch net diameter
0.010-inch root radius, r
60° flank angle, ω

Surface Condition: Lathe turned to RMS 10

Reference: 2.3.1.3.8(a)

Test Parameters:

Loading—Axial
Frequency—2000 to 2500 cpm
Temperature—RT
Atmosphere—Air

No. of Heats/Lots: 1

Equivalent Stress Equation:

$\text{Log } N_f = 7.14 - 1.74 \log (S_{eq} - 56.4)$
$S_{eq} = S_{max} (1-R)^{0.51}$
Standard Error of Estimate = 0.32
Standard Deviation in Life = 0.59
R^2 = 71%

Sample Size = 29

[Caution: The equivalent stress model may provide unrealistic life predictions for stress ratios beyond those represented above]

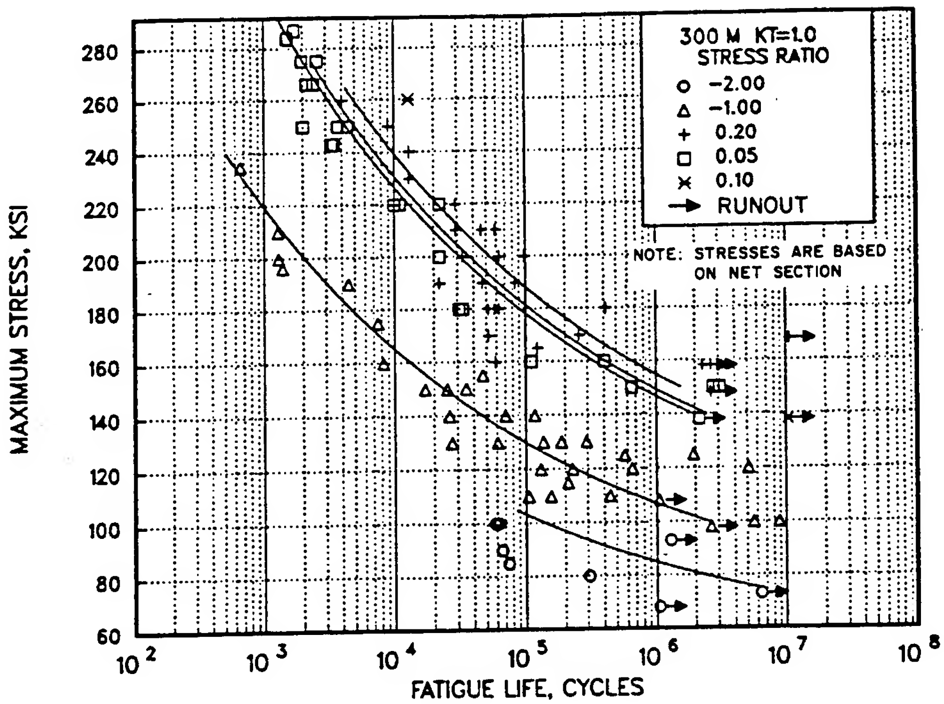


FIGURE 2.3.1.4.8(a). *Best-fit S/N curves for unnotched 300M alloy forging, F_{tu}=280 ksi, longitudinal and transverse directions.*

Correlative Information for Figure 2.3.1.4.8(a)

Product Forms: Die forging, 10 x 20 inches CEVM
Die forging, 6½ x 20 inches CEVM
RCS billet, 6 inches CEVM
Forged Bar, 1¼ x 8 inches CEVM

Properties:

TUS, ksi	TYS, ksi	Temp, F
274-294	227-247	RT

Specimen Details: Unnotched
0.200 - 0.250-inch diameter

Surface Condition: Heat treat and finish grind to a surface finish of RMS 63 or better with light grinding parallel to specimen length, stress relieve

References: 2.3.1.4.8(a), (c), (d), (e)

Test Parameters:
Loading - Axial
Frequency - 1800 to 2000 cpm
Temperature - RT
Atmosphere - Air

No. of Heats/Lots: 6

Equivalent Stress Equation:
$\text{Log } N_f = 14.8 - 5.38 \text{ Log } (S_{eq} - 63.8)$
$S_{eq} = S_a + .48S_m$
Standard Deviation in Log (Life) = 55.7 ($1/S_{eq}$)
Adjusted R^2 = 82.0

Sample Size: 104

[Caution: The equivalent stress model may provide unrealistic life predictions for stress ratios beyond those represented above]

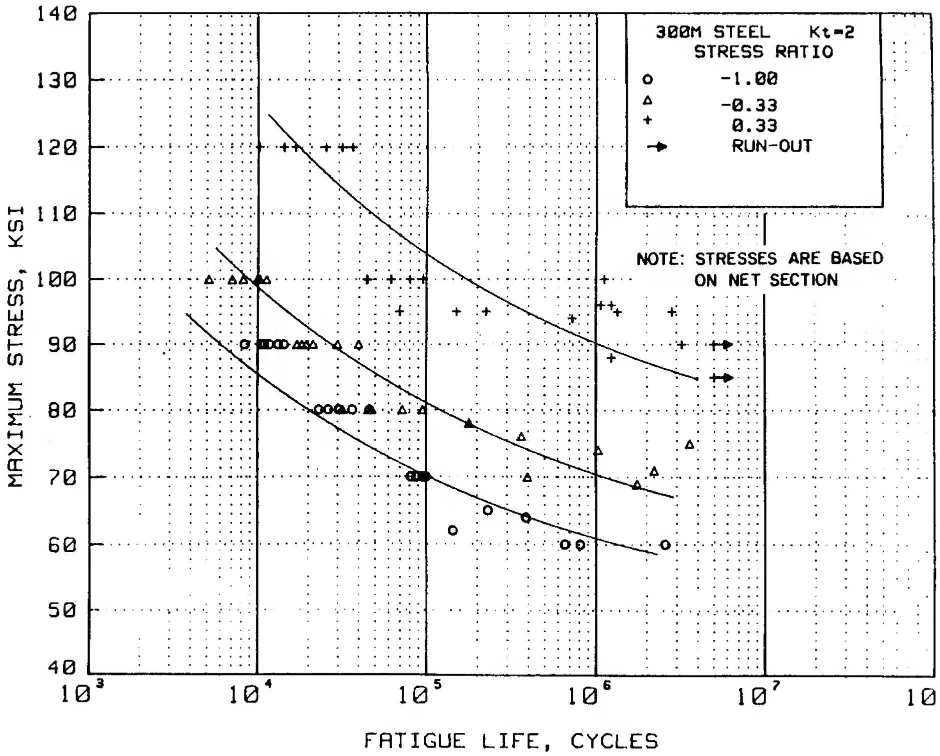


FIGURE 2.3.1.4.8(b). *Best-fit S/N curves for notched, K_t=2.0, 300M alloy forged billet, F_{tu}=280 ksi, longitudinal direction.*

Correlative Information for Figure 2.3.1.4.8(b)

Product Forms: Forged billet, unspecified size, CEVM

Properties:	TUS, ksi	TYS, ksi	Temp, F
	290	242	RT (unnotched)
	456	--	RT (notched)

Specimen Details: Notched, 60° V-Groove, K_t=2.0
0.500-inch gross diameter
0.250-inch net diameter
0.040-inch root radius, r
60° flank angle, ω

Surface Condition: Heat treat and finish grind notch to RMS 63 ± 5; stress relieve

References: 2.3.1.4.8(b)

Test Parameters:
Loading - Axial
Frequency -
Temperature - RT
Atmosphere - Air

No. of Heats/Lots: 3

Equivalent Stress Equation:
$\text{Log } N_f = 12.87 - 5.08 \log (S_{eq} - 55.0)$
$S_{eq} = S_{max} (1-R)^{0.36}$
Standard Deviation in Life = 0.79
R^2 = 79%

Sample Size: 70

[Caution: The equivalent stress model may provide unrealistic life predictions for stress ratios beyond those represented above]

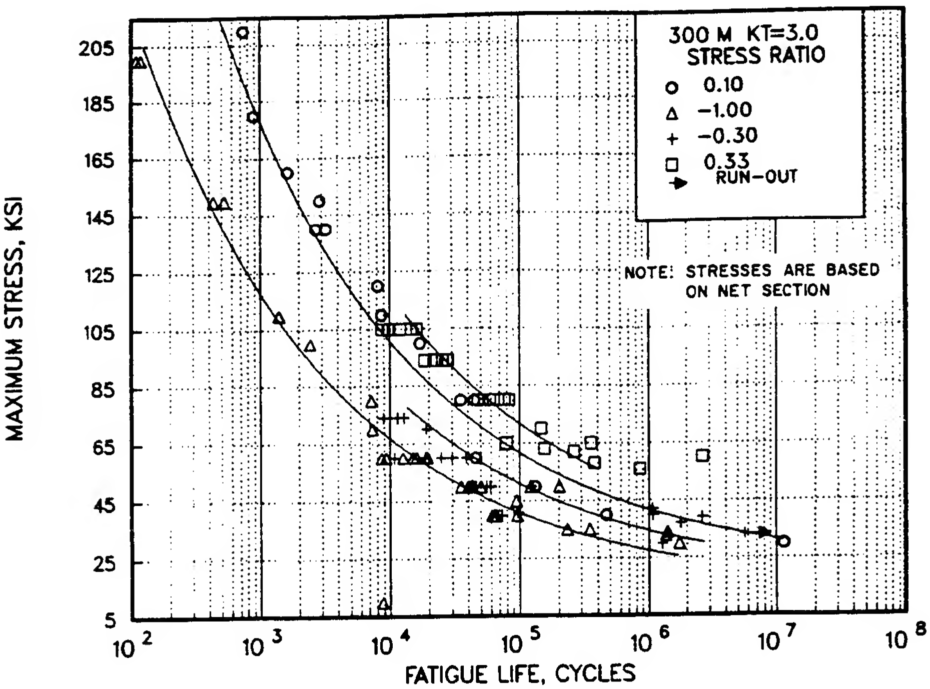


FIGURE 2.3.1.4.8(c). *Best-fit S/N curves for notched, K_t=3.0, 300M alloy forging, F_{tu}=280 ksi, longitudinal and transverse directions.*

Correlative Information for Figure 2.3.1.4.8(c)

Product Forms: Forged billet, unspecified size, CEVM
Die forging, 10 x 20 inches CEVM
Die forging, 6½ x 20 inches, CEVM

Properties:	TUS, ksi	TYS, ksi	Temp, F
	290-292	242-247	RT (unnotched)
	435	--	RT (notched)

Specimen Details: Notched 60° V-Groove, K_t=3.0
0.500-inch gross diameter
0.250-inch net diameter
0.0145-inch root radius, r
60° flank angle, ω

Surface Condition: Heat treat and finish grind notch to RMS 63 or better; stress relieve

References: 2.3.1.4.8(a), (b), (c)

Test Parameters:
Loading - Axial
Frequency -
Temperature - RT
Atmosphere - Air

No. of Heats/Lots: 5

Equivalent Stress Equation:
Log N_f = 10.40 - 3.41 Log (S_{eq} - 20.0)
$S_{eq} = S_{max} (1-R)^{0.51}$
Standard Deviation in Log (Life) = 18.3 (1/S_{eq})
Adjusted R^2 = 97.4

Sample Size: 99

[Caution: The equivalent stress model may provide unrealistic life predictions for stress ratios beyond those represented above]

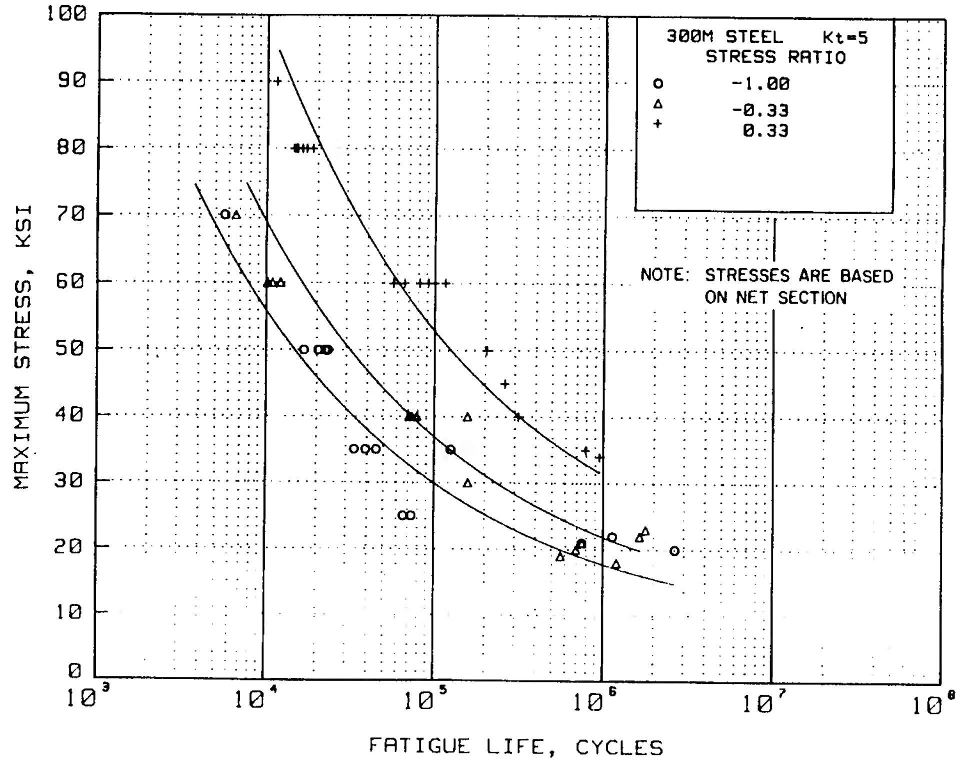


FIGURE 2.3.1.4.8(d). *Best-fit S/N curves for notched, K_t=5.0, 300M alloy forged billet, F_{tu}=280 ksi, longitudinal direction.*

Correlative Information for Figure 2.3.1.4.8(d)

Product Forms: Forged billet, unspecified size, CEVM

Properties:

TUS, ksi	TYS, ksi	Temp, F
290	242	RT (unnotched)
379	--	RT (notched)

Specimen Details: Notched, 60° V-Groove, K_t=5.0
0.500-inch gross diameter
0.250-inch net diameter
0.0042-inch root radius, r
60° flank angle, ω

Surface Condition: Heat treat and finish grind notch to RMS 63 maximum; stress relieve

References: 2.3.1.4.8(b)

Test Parameters:
Loading - Axial
Frequency -
Temperature - RT
Atmosphere - Air

No. of Heats/Lots: 2

Equivalent Stress Equation:
$\log N_f = 9.61 - 3.04 \log (S_{eq} - 10.0)$
$S_{eq} = S_{max} (1-R)^{0.52}$
Standard Error of Estimate = 0.28
Standard Deviation in Life = 0.81
R^2 = 88%

Sample Size: 48

[Caution: The equivalent stress model may provide unrealistic life predictions for stress ratios beyond those represented above]

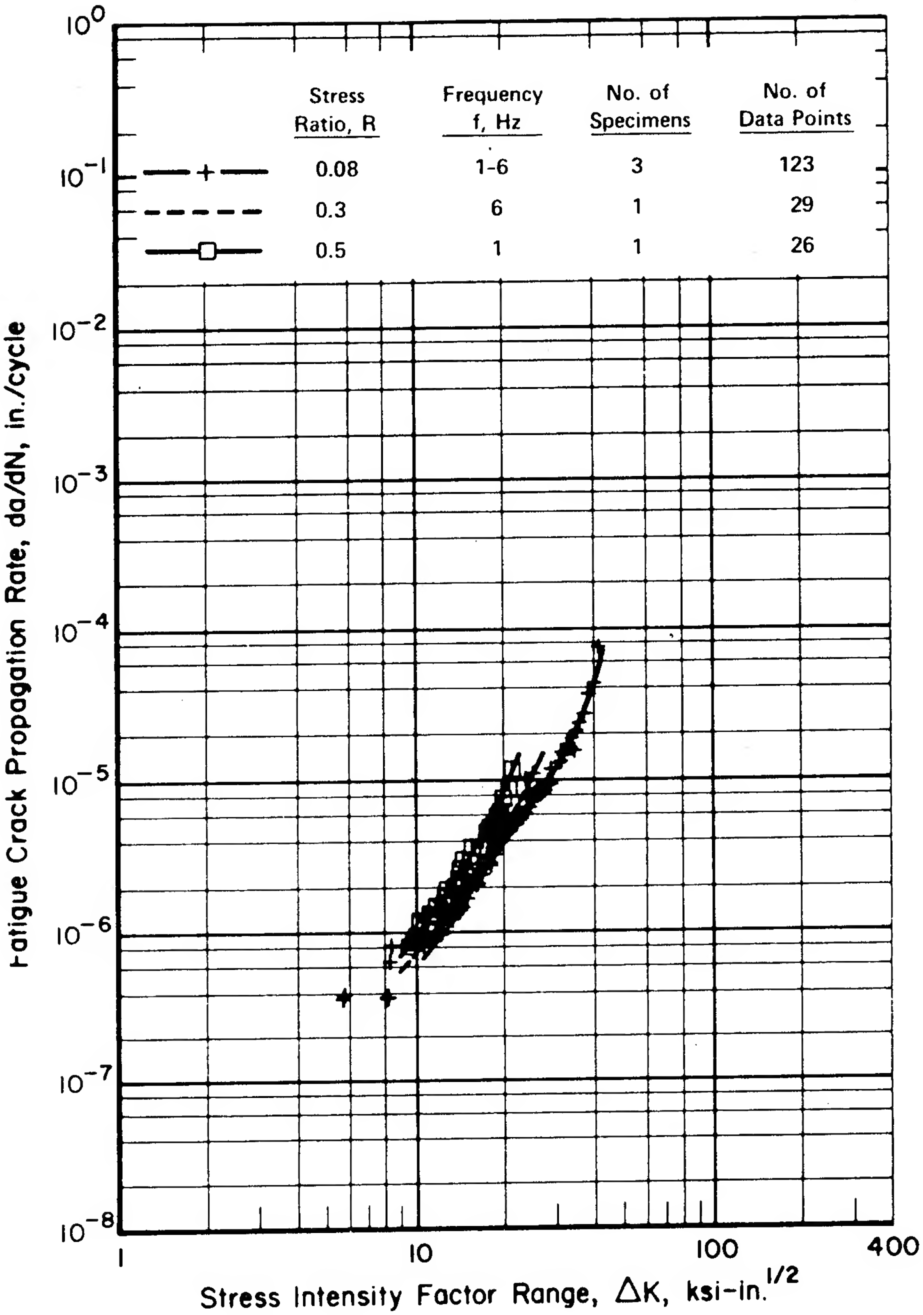


FIGURE 2.3.1.4.9. *Fatique-crack-propagation data for 3.00 inch hand forging and 1.80 inch thick, 300M steel alloy plate (TUS: 280-290 ksi). [References - 2.3.1.4.9(a) and (b)].*

Specimen Thickness:	*0.900-1.000 inches*	*Environment:*	*Low-humidity air*
Specimen Width:	*3.09-7.41 inches*	*Temperature:*	*RT*
Specimen Type:	*CT*	*Orientation:*	*L-T and T-L*

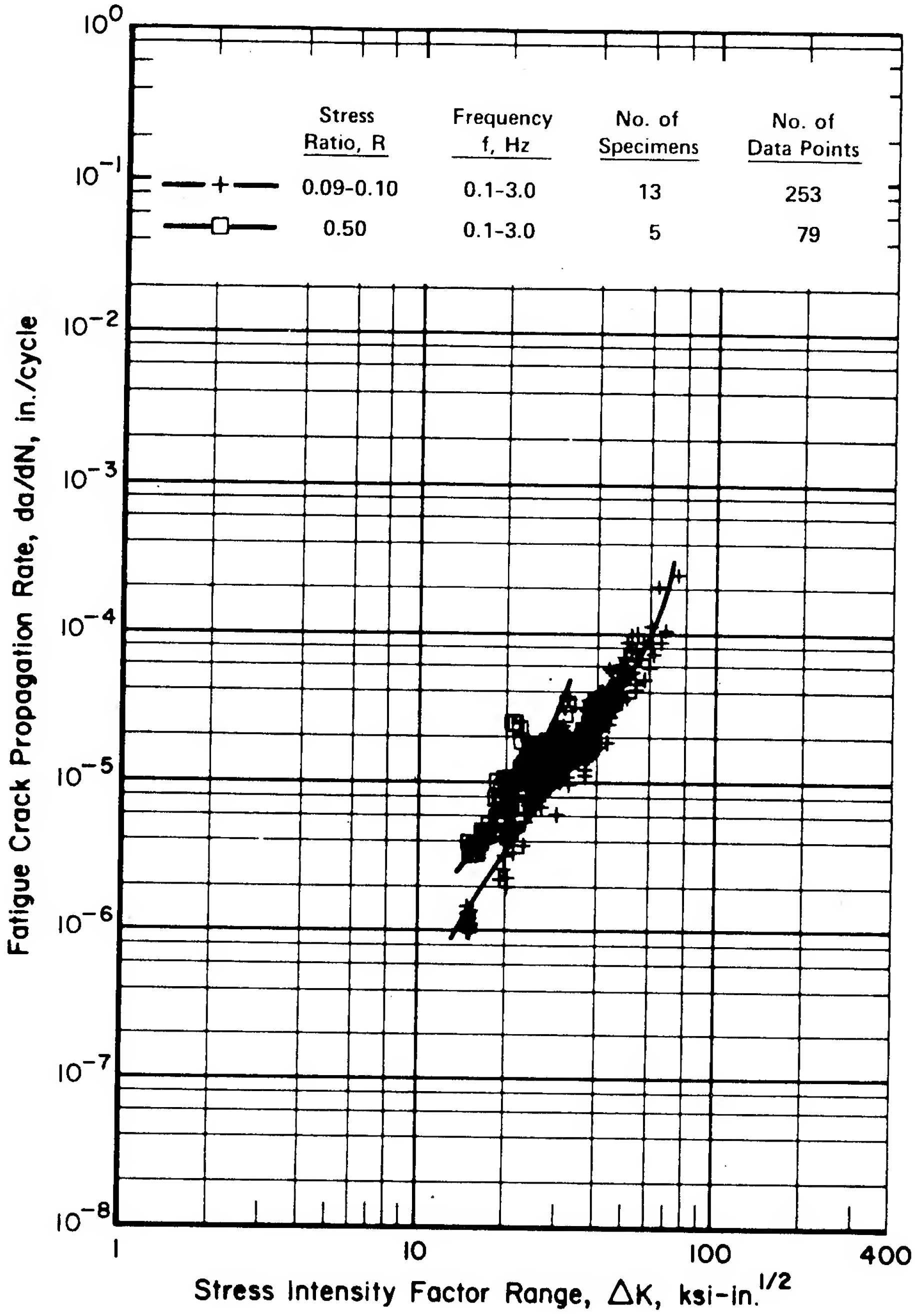


FIGURE 2.3.1.5.9. *Fatique-crack-propagation data for 0.80 inch D6AC steel alloy plate. Data include material both oil quenched and salt quenched from aus-bay temperature (TUS: 230-240 ksi). [References - 2.3.1.5.9].*

Specimen Thickness:	*0.70-0.75 inch*	*Environment:*	*Dry air and lab air*
Specimen Width:	*1.5-5.0 inches*	*Temperature:*	*RT*
Specimen Type:	*CT*	*Orientation:*	*L-T*

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2.4 Intermediate Alloy Steels

2.4.0 COMMENTS ON INTERMEDIATE ALLOY STEELS.—The intermediate alloy steels in this section are those steels that are substantially higher in alloy content than the alloy steels described in Section 2.3, but lower in alloy content than the stainless steels. Typical of the intermediate alloy steels is the 5Cr-Mo-V aircraft steel and the 9Ni-4Co series of steels.

2.4.0.1 *Metallurgical Considerations.*—The alloying elements added to these steels are similar to those used in the lower alloy steels and, in general, have the same effects. The difference lies in the quantity of alloying additions and the extent of these effects. Thus, higher chromium contents provide improved oxidation resistance. Additions of molybdenum, vanadium, and tungsten, together with the chromium, provide deep air-hardening properties and improve the elevated-temperature strength by retarding the rate of tempering at high temperatures. Additions of nickel to nonsecondary hardening steels lower the transition temperature and improve low-temperature toughness.

2.4.1 5Cr-Mo-V

2.4.1.0 *Comments and Properties.*—Alloy 5Cr-Mo-V aircraft steel exhibits high strength in the temperature range up to 1000 F. Its characteristics also include air hardenability in thick sections; consequently, little distortion is encountered in heat treatment. This steel is available either as air-melted or consumable electrode vacuum-melted quality although only consumable electrode vacuum-melted quality is recommended for aerospace applications.

The heat treatment recommended for this steel consists of heating to 1850 F ± 50, holding 15 to 25 minutes for sheet or 30 to 60 minutes for bars depending on section size, cooling in air to room temperature, tempering three times by heating to the temperature specified in Table 2.4.1.0(a) for the strength level desired, holding at temperature for 2 to 3 hours, and cooling in air.

TABLE 2.4.1.0(a). *Tempering Temperatures for 5Cr-Mo-V Aircraft Steel*

F_{tu}, ksi	Temperature, F	Hardness, R_c
280	1000 ± 10	54-56
260	1030 ± 10	52-54
240	1050 ± 10	49-52
220	1080 ± 10	46-49

Material specifications for 5Cr-Mo-V aircraft steel are presented in Table 2.4.1.0(b). The room-temperature mechanical and physical properties are shown in Tables 2.4.1.0(c) and (d). The mechanical properties are for 5Cr-Mo-V steel heat treated to produce a structure containing 90 percent or more martensite at the center prior to tempering.

TABLE 2.4.1.0(b). *Material Specifications for 5Cr-Mo-V Aircraft Steel*

Specification	Form
AMS 6437	Sheet, strip, and plate (air melted)
AMS 6485	Bar and forging (air melted)
AMS 6488	Bar and forging (air melted, premium quality)
AMS 6487	Bar and forging (CEVM)

The room-temperature properties of 5Cr-Mo-V aircraft steel are affected by extended exposure to temperatures near or above the tempering temperature. The limiting temperature to which the alloy may be exposed for extended periods without significantly affecting its room-temperature properties may be estimated at 100 F below the tempering temperature for the desired strength level. The effect of temperature on the physical properties is shown in Figure 2.4.1.0.

2.4.1.1 *Heat-Treated Condition.*—The effect of temperature on various mechanical properties for heat-treated 5Cr-Mo-V aircraft steel is presented in Figures 2.4.1.1.1(a) through 2.4.1.1.4. In addition elevated temperature requirements are specified in AMS 6437 and 6485.

TABLE 2.4.1.0(c). *Design Mechanical and Physical Properties of 5Cr-Mo-V Aircraft Steel Bar and Forging*

Specification	AMS 6485		
Form	Bars and forgings		
Condition	Quenched and tempered		
Cross-sectional area, in.^{2}	b,c		
Basis	S[a]	S[a]	S[a]
Mechanical Properties:			
F_{tu}, ksi:			
L	...	260[b]	...
T	240	260[c]	280
F_{ty}, ksi:			
L	...	215[b]	...
T	200	215[c]	240
F_{cy}, ksi:			
L	...	...	...
T	220	234	260
F_{su}, ksi	144	156	168
F_{bru}, ksi:			
(e/D = 1.5)	...	...	...
(e/D = 2.0)	400	435	465
F_{bry}, ksi:			
(e/D = 1.5)	...	...	...
(e/D = 2.0)	315	333	365
e, percent:			
L	9	8[b]	7
T	...	...	...
RA, percent:			
L	...	30[b]	...
T	...	c,d	...
E, 10^3 ksi	30.0		
E_c, 10^3 ksi	30.0		
G, 10^3 ksi	11.0		
μ	0.36		
Physical Properties:			
ω, lb/in.^{3}	0.281		
C, Btu/(lb)(F)	0.11 (32 F)		
K and α	See Figure 2.4.1.0		

[a]Design values are applicable only to parts for which the indicated F_{tu} has been substantiated by adequate quality control testing.
[b]Longitudinal properties applicable to cross-sectional area ≤25 sq. in.
[c]Transverse properties applicable to cross-sectional area >25-256 sq. in.
[d]For cross-sectional area >25-100, 6% *RA*; >100-150, 5% *RA*; >150-225, 4% *RA*; >225-256, 3% *RA*.
[e]Calculated.

TABLE 2.4.1.0(d). *Design Mechanical and Physical Properties of 5Cr-Mo-V Aircraft Steel Sheet, Strip, and Plate*

Specification	AMS 6437		
Form	Sheet, strip, and plate		
Condition	Quenched and tempered		
Thickness, in.	...		
Basis	S[a]	S[a]	S[a]
Mechanical Properties:			
F_{tu}, ksi:			
L	...	...	...
LT	240	260	280
F_{ty}, ksi:			
L	...	...	...
LT	200	220	240
F_{cy}, ksi:			
L	...	...	...
LT	220	240	260
F_{su}, ksi	144	156	168
F_{bru}, ksi:			
(e/D = 1.5)	...	...	...
(e/D = 2.0)	400	435	465
F_{bry}, ksi:			
(e/D = 1.5)	...	...	...
(e/D = 2.0)	315	340	365
e, percent:			
L	...	...	...
LT, in 2 inches[b]	6	5	4
LT, in 1 inch	8	7	6
E, 10^3 ksi	30.0		
E_c, 10^3 ksi	30.0		
G, 10^3 ksi	11.0		
μ	0.36		
Physical Properties:			
ω, lb/in.^{3}	0.281		
C, Btu/(lb)(F)	0.11[c] (32 F)		
K and α	See Figure 2.4.1.0		

[a]Design values are applicable only to parts for which the indicated F_{tu} has been substantiated by adequate quality control testing.
[b]For sheet thickness greater than 0.050 inch.
[c]Calculated value.

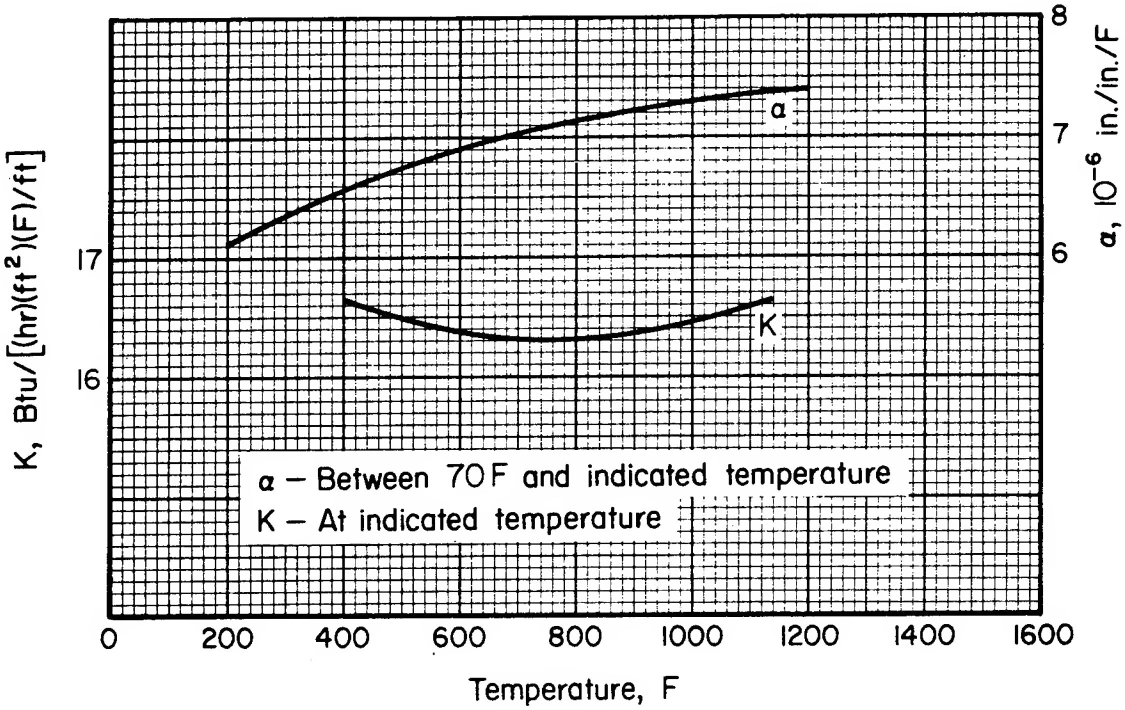

FIGURE 2.4.1.0. *Effect of temperature on the physical properties of 5Cr-Mo-V aircraft steel.*

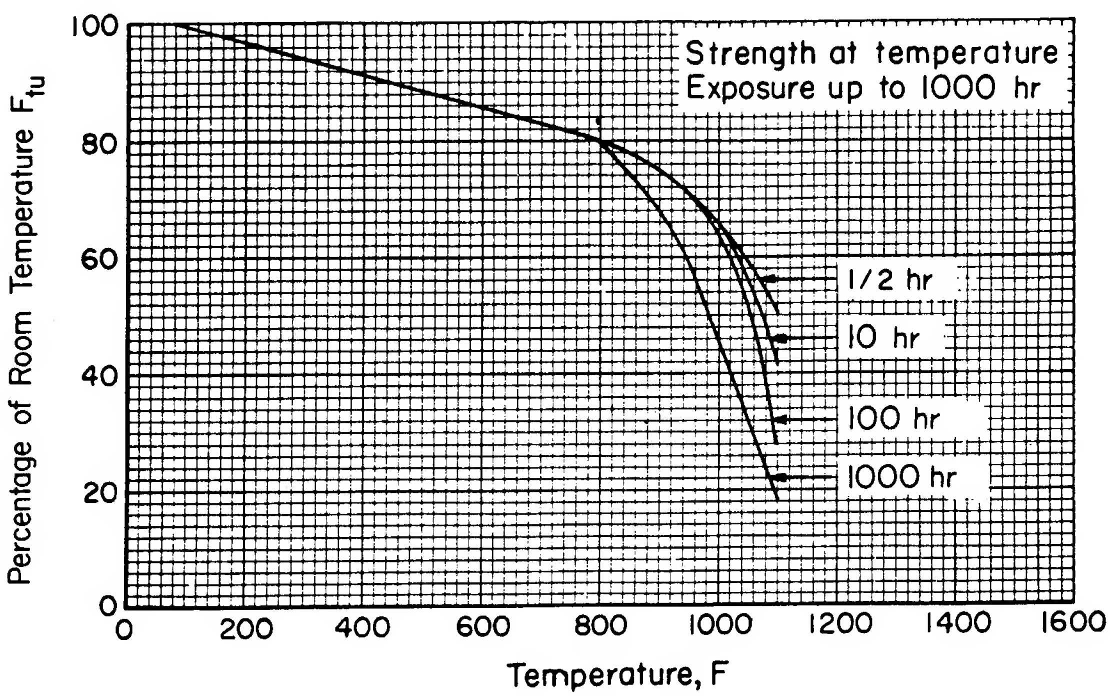

FIGURE 2.4.1.1.1(a). *Effect of temperature on the ultimate tensile strength (F_{tu}) of 5Cr-Mo-V aircraft steel.*

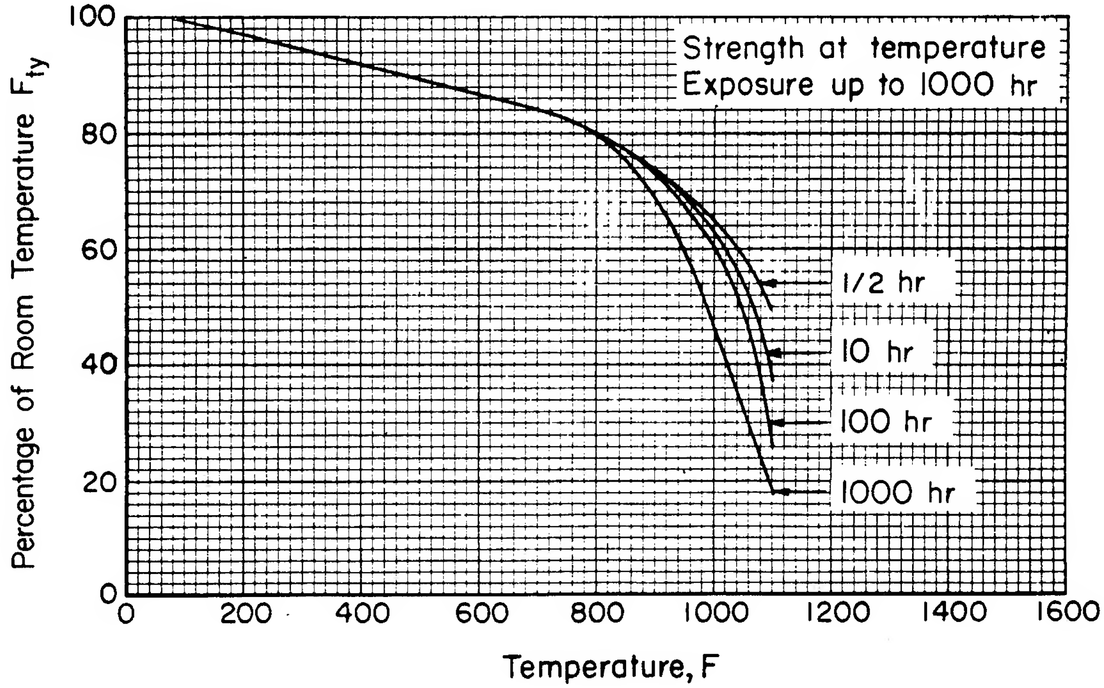

FIGURE 2.4.1.1.1(b). *Effect of temperature on the tensile yield strength (F_{ty}) of 5Cr-Mo-V aircraft steel.*

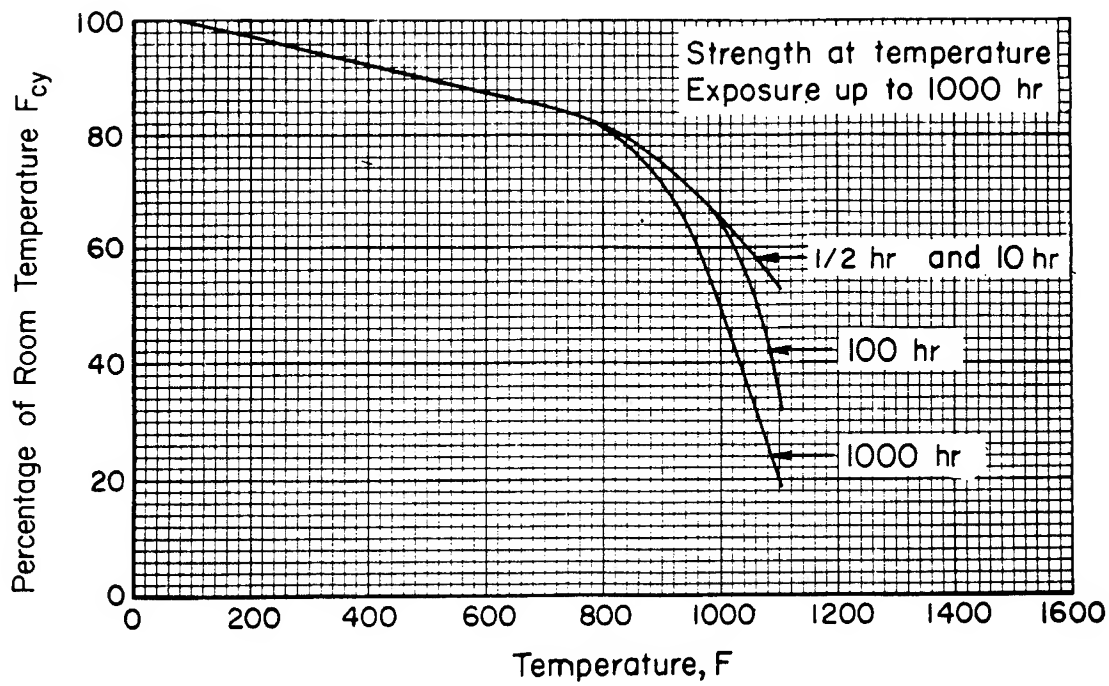

FIGURE 2.4.1.1.2(a). *Effect of temperature on the compressive yield strength (F_{cy}) of 5Cr-Mo-V aircraft steel.*

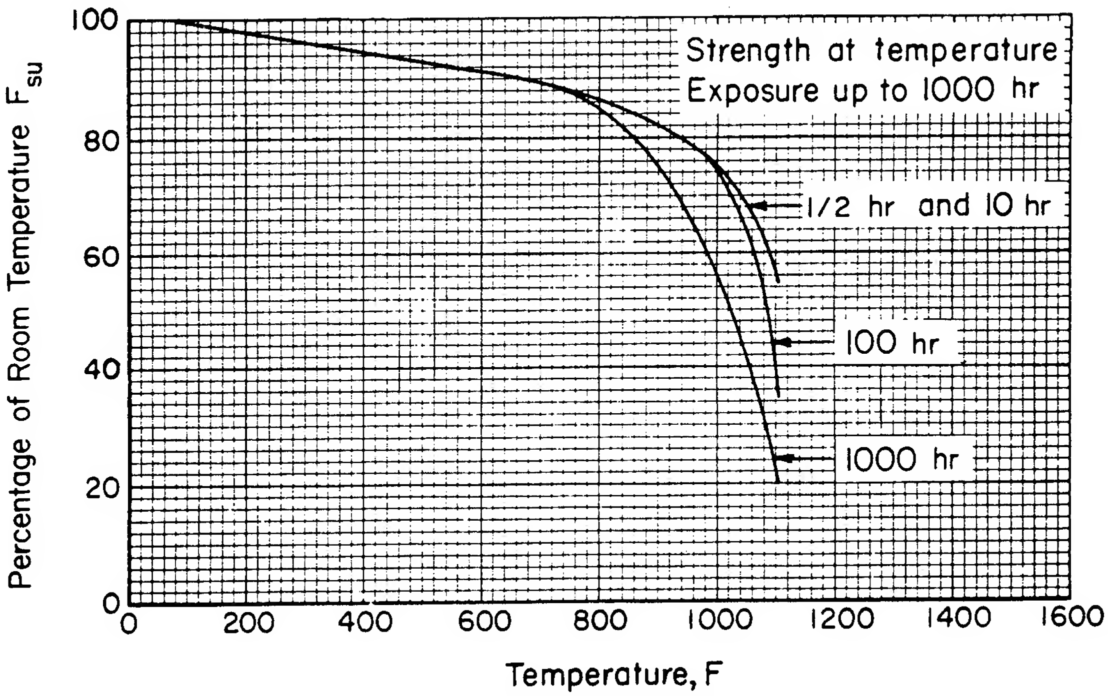

FIGURE 2.4.1.1.2(b). *Effect of temperature on the ultimate shear strength (F_{su}) of 5Cr-Mo-V aircraft steel.*

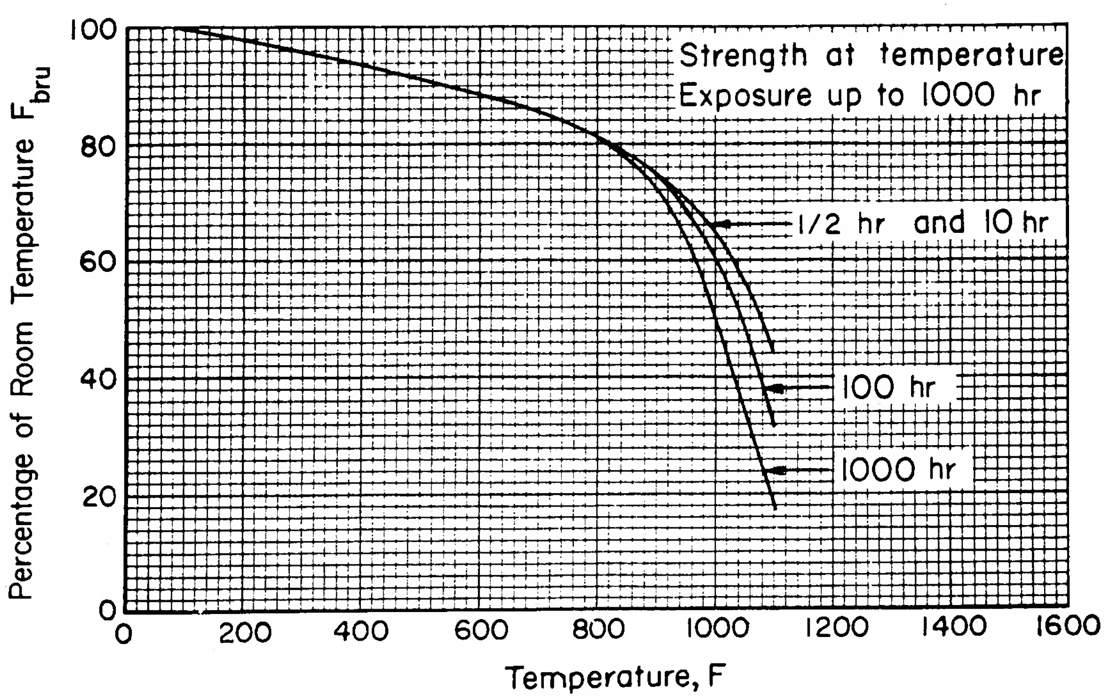

FIGURE 2.4.1.1.3(a). *Effect of temperature on the ultimate bearing strength (F_{bru}) of 5Cr-Mo-V aircraft steel.*

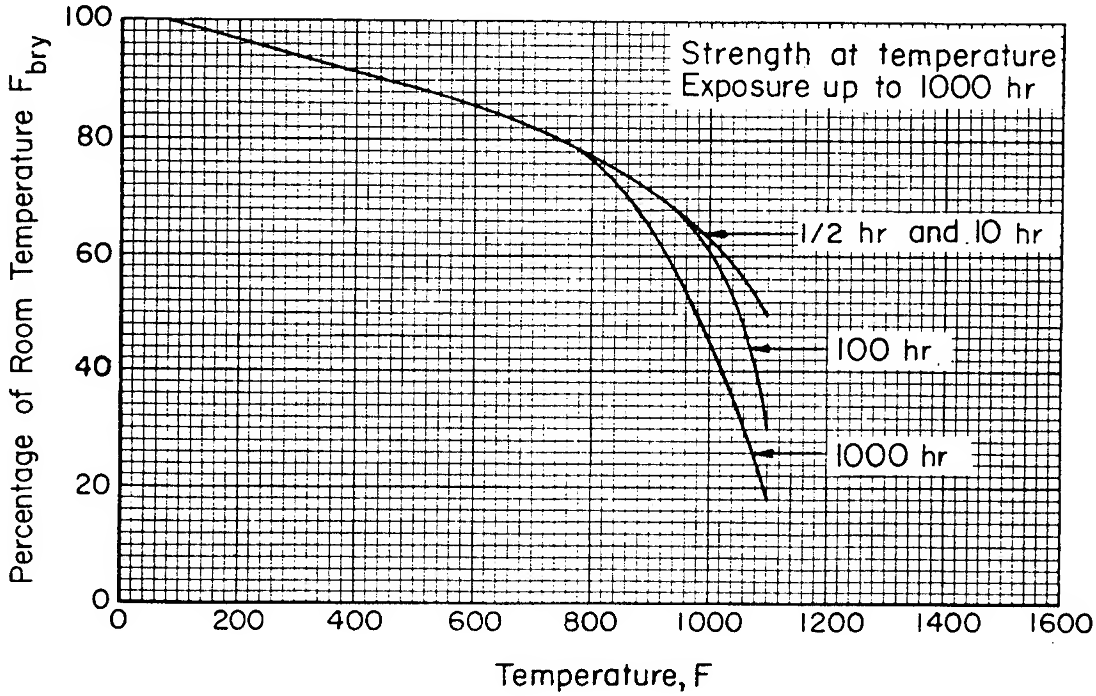

FIGURE 2.4.1.1.3(b). *Effect of temperature on the bearing yield strength (F_{bry}) of 5Cr-Mo-V aircraft steel.*

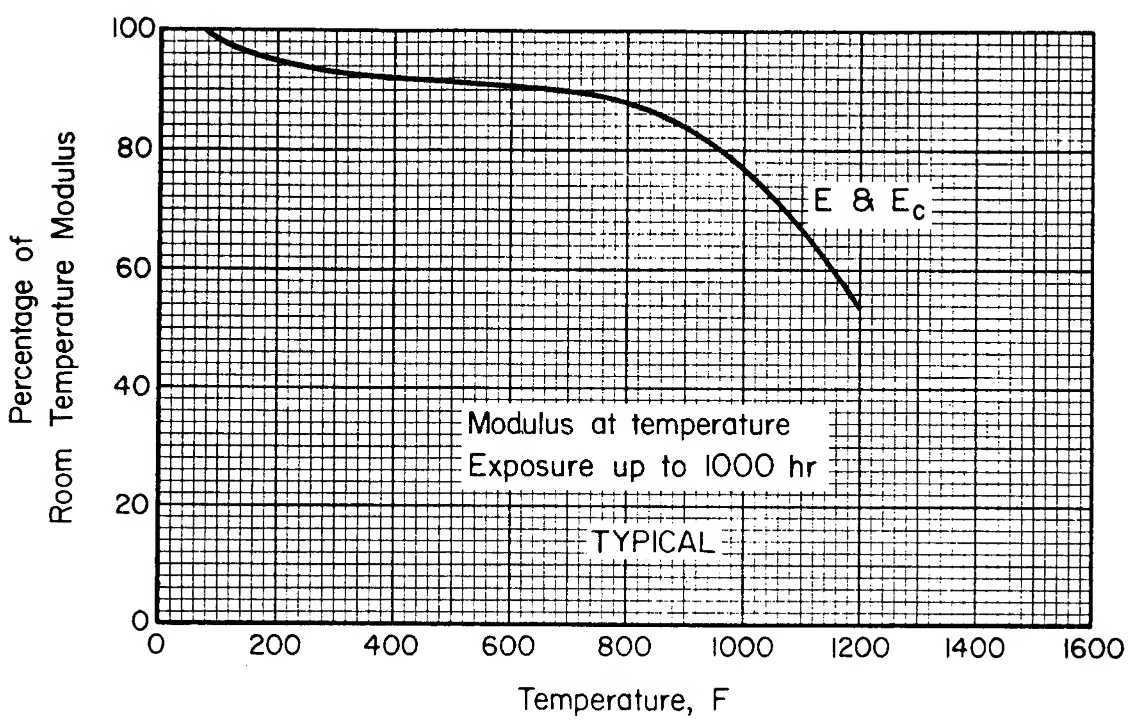

FIGURE 2.4.1.1.4. *Effect of temperature on the tensile and compressive moduli (E and E_c) of 5Cr-Mo-V aircraft steel.*

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2.4.2 9Ni-4Co-0.20C

2.4.2.0 *Comments and Properties.*—The 9Ni-4Co-0.20C alloy was developed specifically to have excellent fracture toughness, excellent weldability, and high hardenability when heat-treated to 190 to 210 ksi ultimate tensile strength. The alloy can be readily welded in the heat-treated condition with preheat and post-heat usually not required. The alloy is through hardening in section sizes up to at least 8 inches thick. The alloy may be exposed to temperatures up to 900 F (approximately 100 F below typical tempering temperature) without microstructural changes which degrade room temperature strength.

The heat treatment for this alloy consists of normalizing at 1650 ± 25 F for 1 hour per inch of cross section, cooling in air to room temperature, heating to 1525 ± 25 F for 1 hour per inch of cross section, quenching in oil or water, hold at -100 ± 20 F for 2 hours within 2 hours after quenching, and double tempering at 1035 ± 10 F for 2 hours.

A material specification for 9Ni-4Co-0.20C steel is presented in Table 2.4.2.0(a). Room temperature mechanical and physical properties are shown in Table 2.4.2.0(b). The effect of temperature on thermal expansion is shown in Figure 2.4.2.0.

TABLE 2.4.2.0(a). *Material Specification for 9Ni-4Co-0.20C Steel*

Specification	Form
AMS 6523	Sheet, strip, and plate

2.4.2.1 *Heat-Treated Condition.*—Effect of temperature on various mechanical properties is presented in Figures 2.4.2.1.1, 2.4.2.1.2, and 2.4.2.1.4. Typical tensile stress-strain curves at room and elevated temperatures are shown in Figure 2.4.2.1.6(a). Typical compression stress-strain and tangent-modulus curves are presented in Figure 2.4.2.1.6(b).

TABLE 2.4.2.0(b). *Design Mechanical and Physical Properties of 9Ni-4Co-.20C Steel Plate*

Specification	AMS 6523	
Form	Plate	
Condition	Quenched and tempered	
Thickness, in.	<0.250	≥0.250
Basis	S[a]	S[a]
Mechanical Properties:		
F_{tu}, ksi:		
L	186	186
LT	190	190
F_{ty}, ksi:		
L	173	173
LT	175	175
F_{cy}, ksi:		
L	188	188
LT	187	187
F_{su}, ksi	114	114
F_{bru}, ksi:		
(e/D = 1.5)	...	...
(e/D = 2.0)	...	...
F_{bry}, ksi:		
(e/D = 1.5)	...	...
(e/D = 2.0)	...	...
e, percent:		
LT	5	10
RA, percent:		
LT	45	45
E, 10^3 ksi	28.8	
E_c, 10^3 ksi	28.8	
G, 10^3 ksi	11.1	
μ	0.30	
Physical Properties:		
ω, lb/in.^{3}	0.283	
C, Btu/(lb)(F)	...	
K, Btu/[(hr)(ft^2)(F)/ft]	14.2 (75 F)	
α, 10^{-6} in./in./F	See Figure 2.4.2.0	

[a]Design values are applicable only to parts for which the indicated F_{tu} has been substantiated by adequate quality control testing.

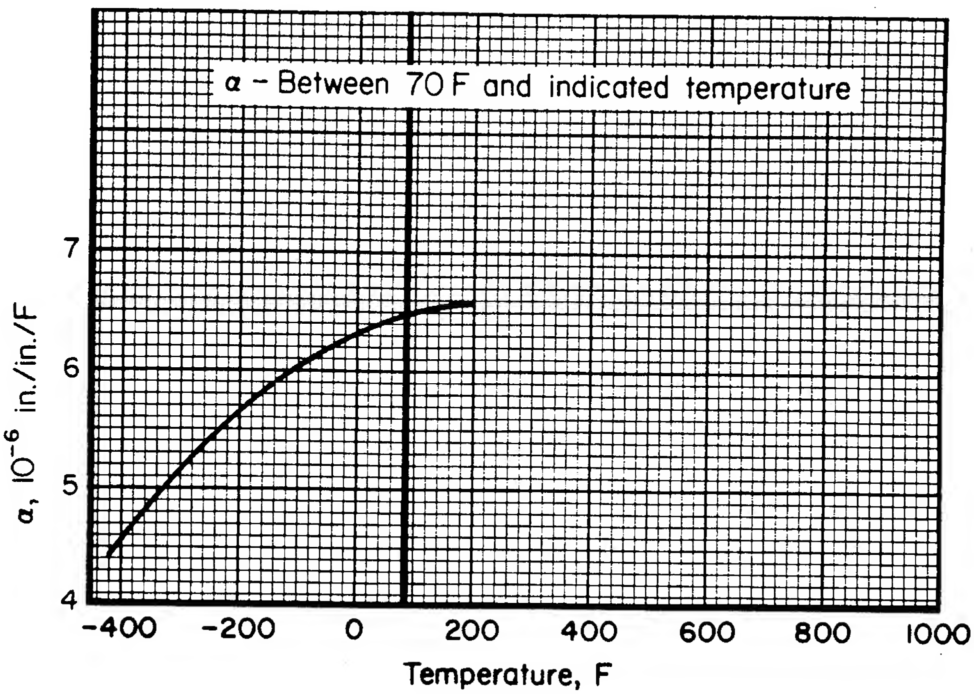

FIGURE 2.4.2.0. *Effect of temperature on the thermal expansion of 9Ni-4Co-.20C steel.*

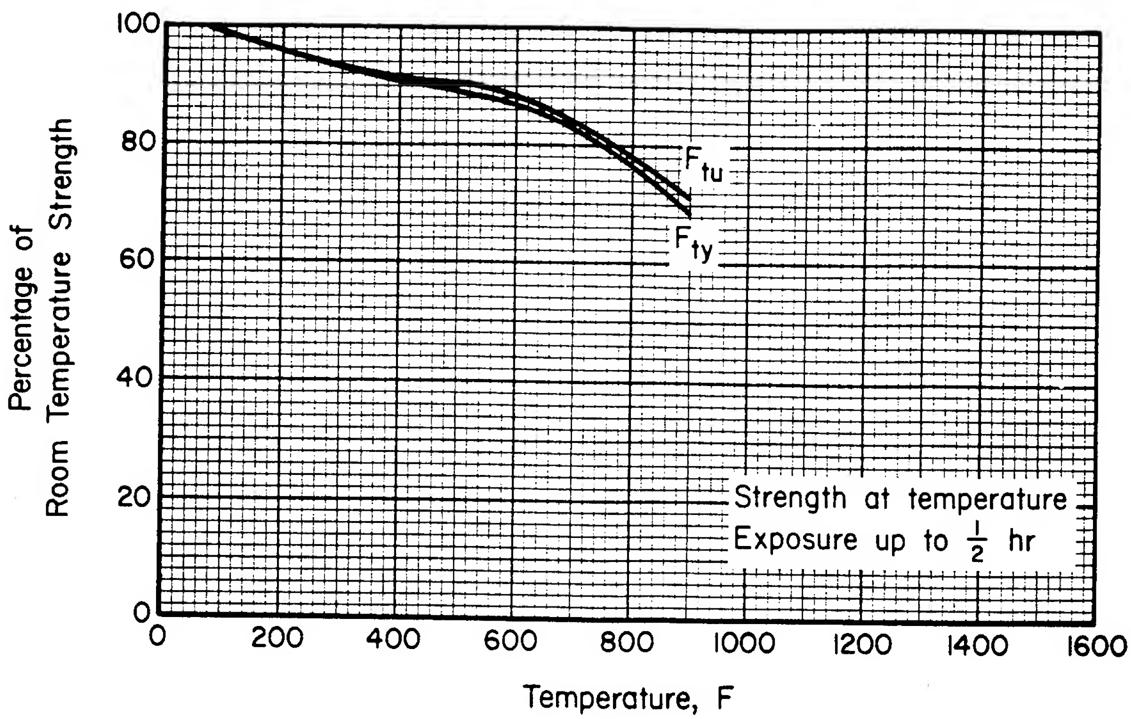

FIGURE 2.4.2.1.1. *Effect of temperature on the tensile ultimate strength (F_{tu}) and tensile yield strength (F_{ty}) of 9Ni-4Co-.20C steel plate.*

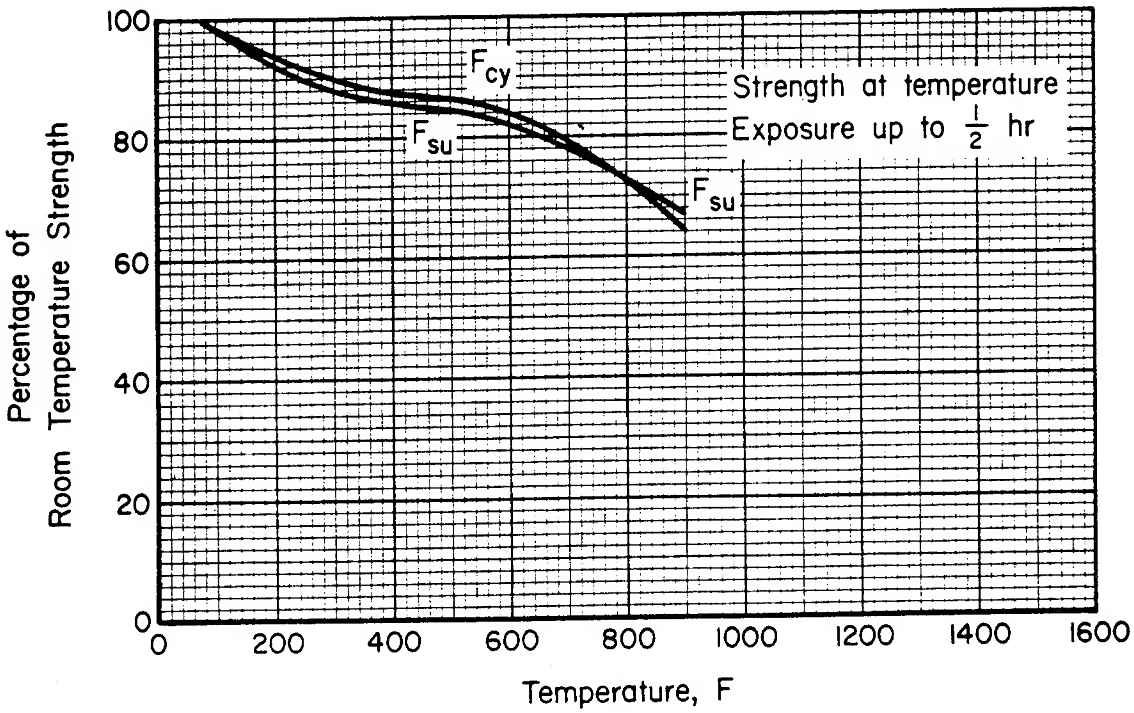

FIGURE 2.4.2.1.2. *Effect of temperature on the compressive yield strength (F_{cy}) and the shear ultimate strength (F_{su}) of 9Ni-4Co-.20C steel plate.*

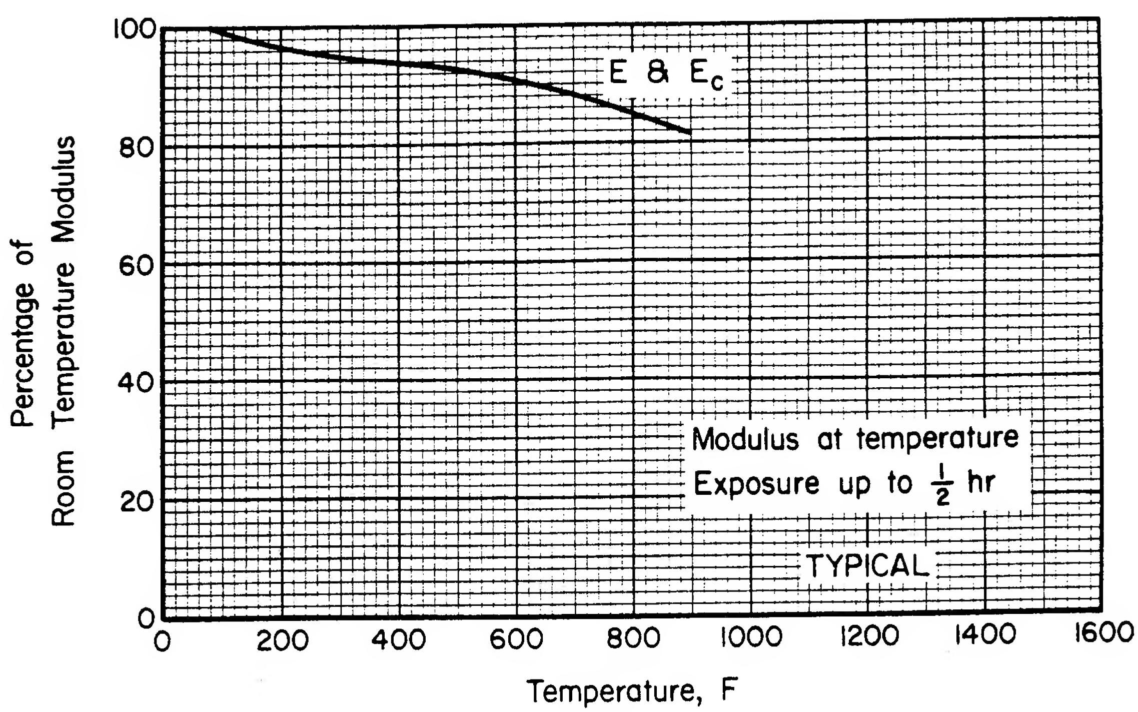

FIGURE 2.4.2.1.4. *Effect of temperature on the tensile and compressive moduli (E and E_c) of 9Ni-4Co-.20C steel plate.*

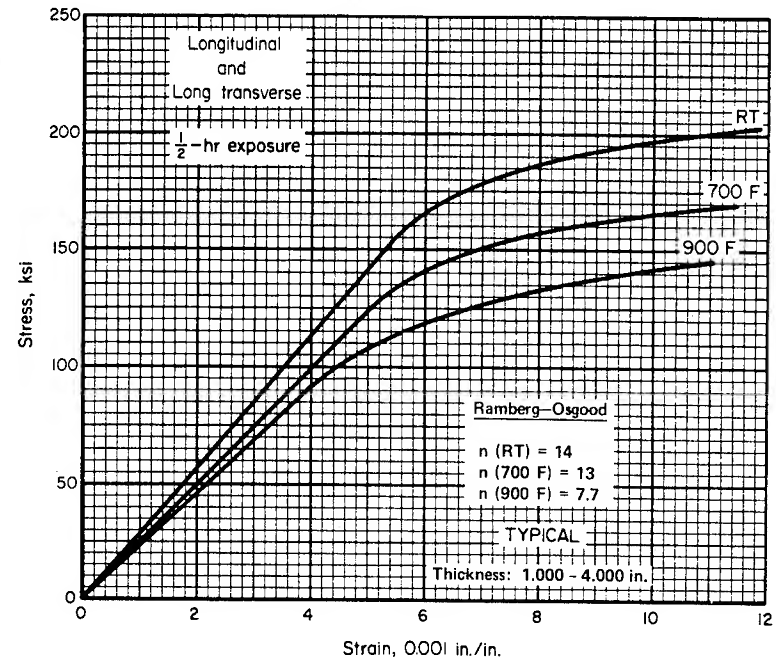

FIGURE 2.4.2.1.6(a). *Typical tensile stress-strain curves for 9Ni-4Co-.20C steel plate at various temperatures.*

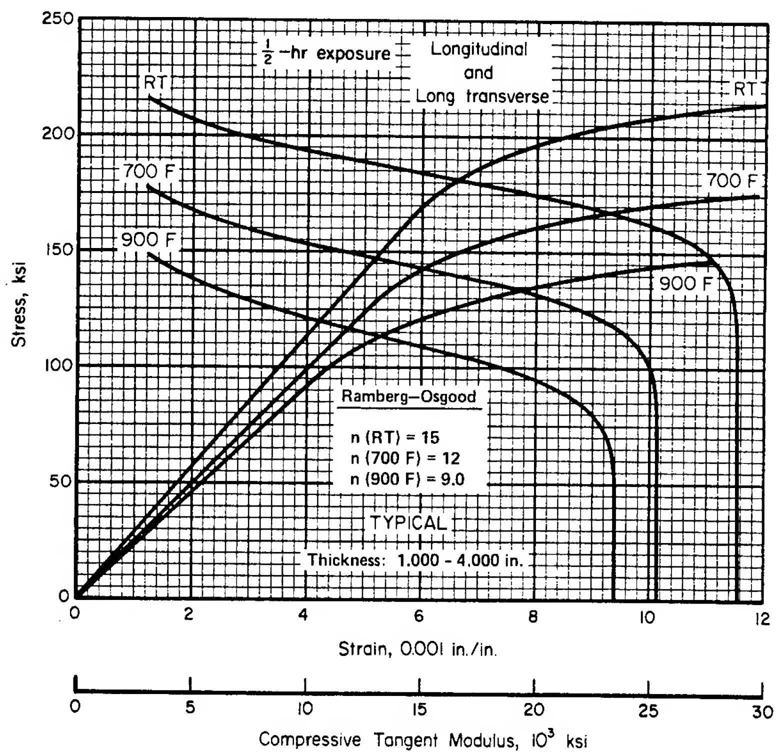

FIGURE 2.4.2.1.6(b). *Typical compressive stress-strain and compressive tangent-modulus curves for 9Ni-4Co-.20C steel plate at various temperatures.*

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2.4.3 9Ni-4Co-0.30C

2.4.3.0 *Comments and Properties.*—The 9Ni-4Co-0.30C alloy was developed specifically to have high hardenability and good fracture toughness when heat treated to 220 to 240 ksi ultimate tensile strength. The alloy is through hardening in section sizes up to 4 inches thick. The alloy may be exposed to temperatures up to 900 F (approximately 100 F below typical tempering temperature) without microstructural changes which degrade room temperature strength. This grade must be formed and welded in the annealed condition. Preheat and post-heat of the weldment is required. The steel is produced by consumable electrode vacuum melting.

The heat treatment for this alloy consists of normalizing at 1650 ± 25 F for 1 hour per inch of cross section, cooling in air to room temperature, heating to 1550 ± 25 F for 1 hour per inch of cross section but not less than 1 hour, quenching in oil or water, subzero treating at -100 F for 1 to 2 hours, and double tempering at 975 ± 10 F (sheet, strip, and plate) or 1000 ± 10 F (bars, forgings, and tubings) for 2 hours.

Material specifications for 9Ni-4Co-0.30C steel are presented in Table 2.4.3.0(a). The room temperature mechanical and physical properties are shown in Table 2.3.4.0(b). The effect of temperature on thermal expansion is shown in Figure 2.4.3.0.

TABLE 2.4.3.0(a). *Material Specifications for 9Ni-4Co-0.30C Steel*

Specification	Form
AMS 6524	Sheet, strip, and plate
AMS 6527	Bar, forging, and tubing

2.4.3.1 *Heat-Treated Condition.*—Effect of temperature on various mechanical properties is presented in Figures 2.4.3.1.1. through 2.4.3.1.4. Typical stress-strain and tangent-modulus curves are presented in Figures 2.4.3.1.6(a) through (d). Notched fatigue data at room temperature are illustrated in Figure 2.4.3.1.8.

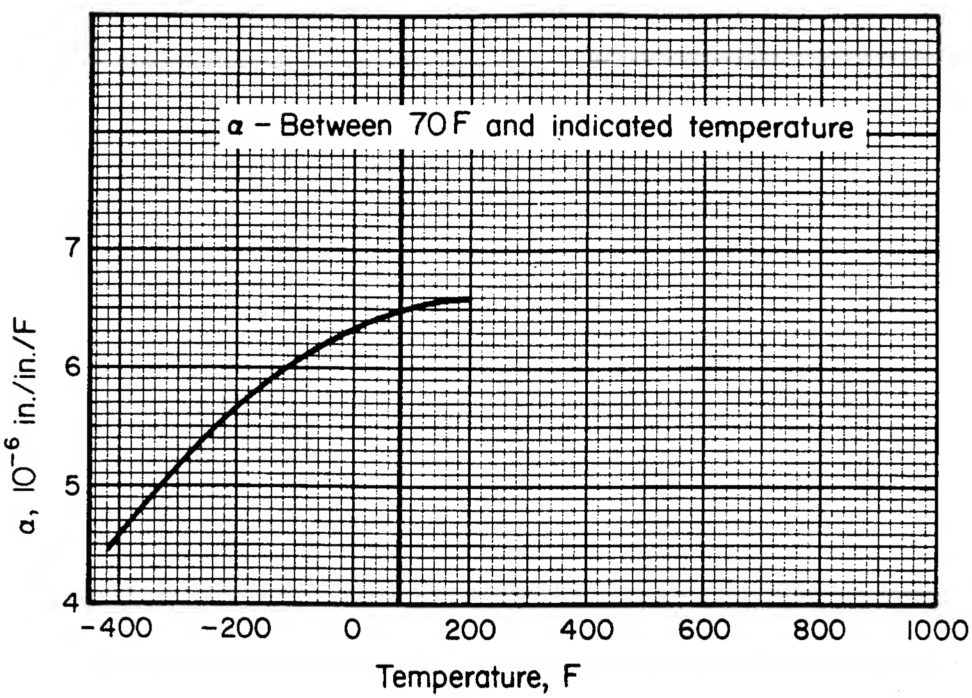

FIGURE 2.4.3.0. *Effect of temperature on the thermal expansion of 9Ni-4Co0.30C steel.*

TABLE 2.4.3.0(b). *Design Mechanical and Physical Properties of 9Ni-4Co-.30C Steel*

Specification	AMS 6524		AMS 6526
Form	Sheet, strip, and plate		Bar, forging, and tubing
Condition	Quenched and tempered		Quenched and tempered
Thickness, in.	≤0.249	≥0.250	≤4.000
Basis	S[a]	S[a]	S[a]
Mechanical Properties:			
F_{tu}, ksi:			
L	...	...	220
LT	220	220	...
F_{ty}, ksi:			
L	...	...	190
LT	185	190	...
F_{cy}, ksi:			
L	...	...	209
LT	...	209	...
F_{su}, ksi	...	137	137
F_{bru}[b], ksi:			
(e/D = 1.5)	...	346	346
(e/D = 2.0)	...	440	440
F_{bry}[b], ksi:			
(e/D = 1.5)	...	291	291
(e/D = 2.0)	...	322	322
e, percent:			
L	...	...	10
LT	6	10	...
RA, percent:			
L	...	...	40
LT	...	35	...
E, 10^3 ksi	28.5		
E_c, 10^3 ksi	29.8		
G, 10^3 ksi	...		
μ	...		
Physical Properties:			
ω, lb/in.^{3}	0.28		
C, Btu/(lb)(F)	...		
K, Btu[(hr)(ft^2)(F)/ft]	160 (75 F)		
α, 10^{-6} in./in./F	See Figure 2.4.3.0		

[a]Design values are applicable only to parts for which the indicated F_{tu} has been substantiated by adequate quality control testing.
[b]Bearing values are "dry pin" values per Section 1.4.7.1.

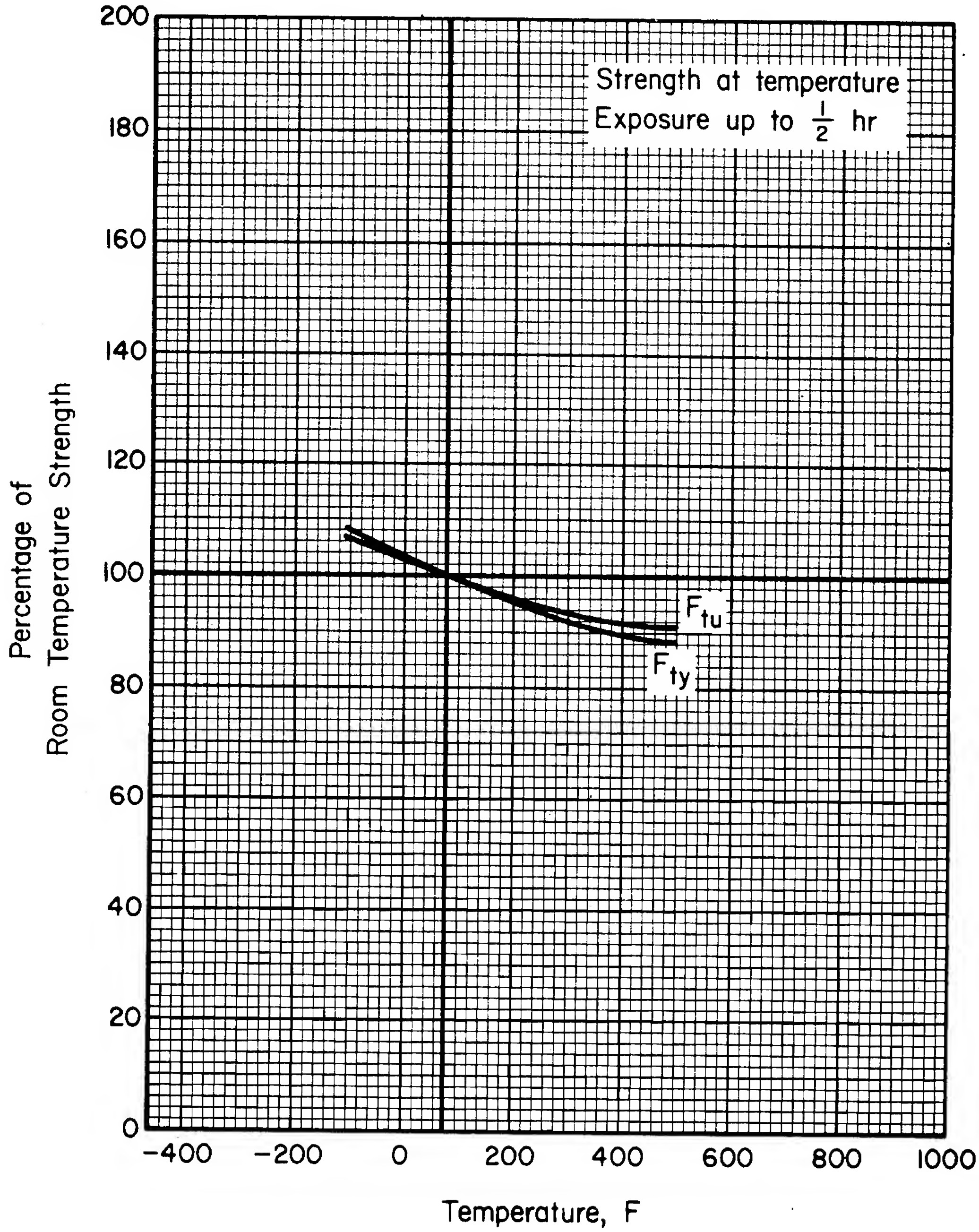

FIGURE 2.4.3.1.1. *Effect of temperature on the tensile yield strength (F_{ty}) and the tensile ultimate strength of 9Ni-4Co-.30C steel hand forging.*

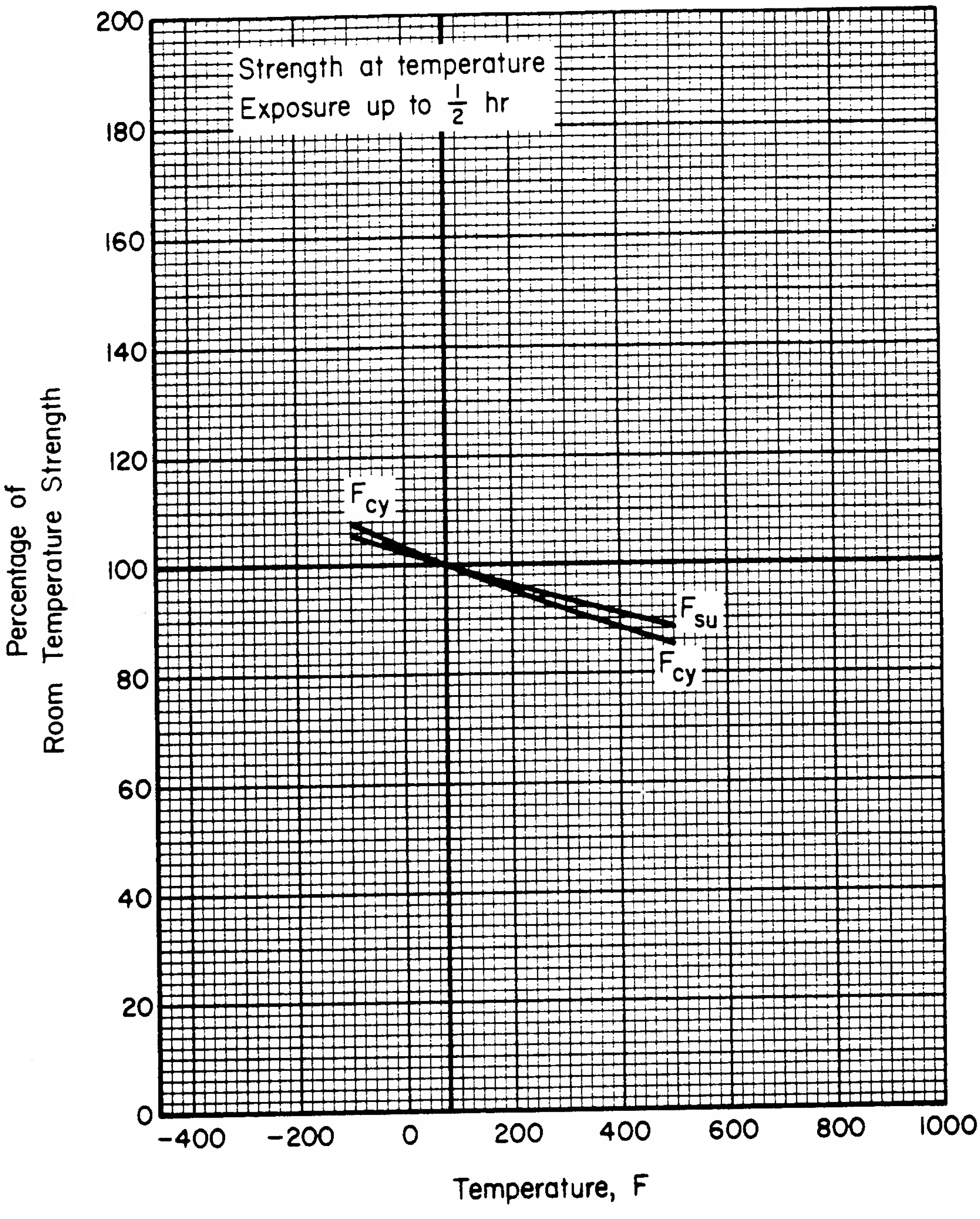

FIGURE 2.4.3.1.2. *Effect of temperature on the compressive yield strength (F_{cy}) and the shear ultimate strength (F_{su}) of 9Ni-4Co-.30C steel hand forging.*

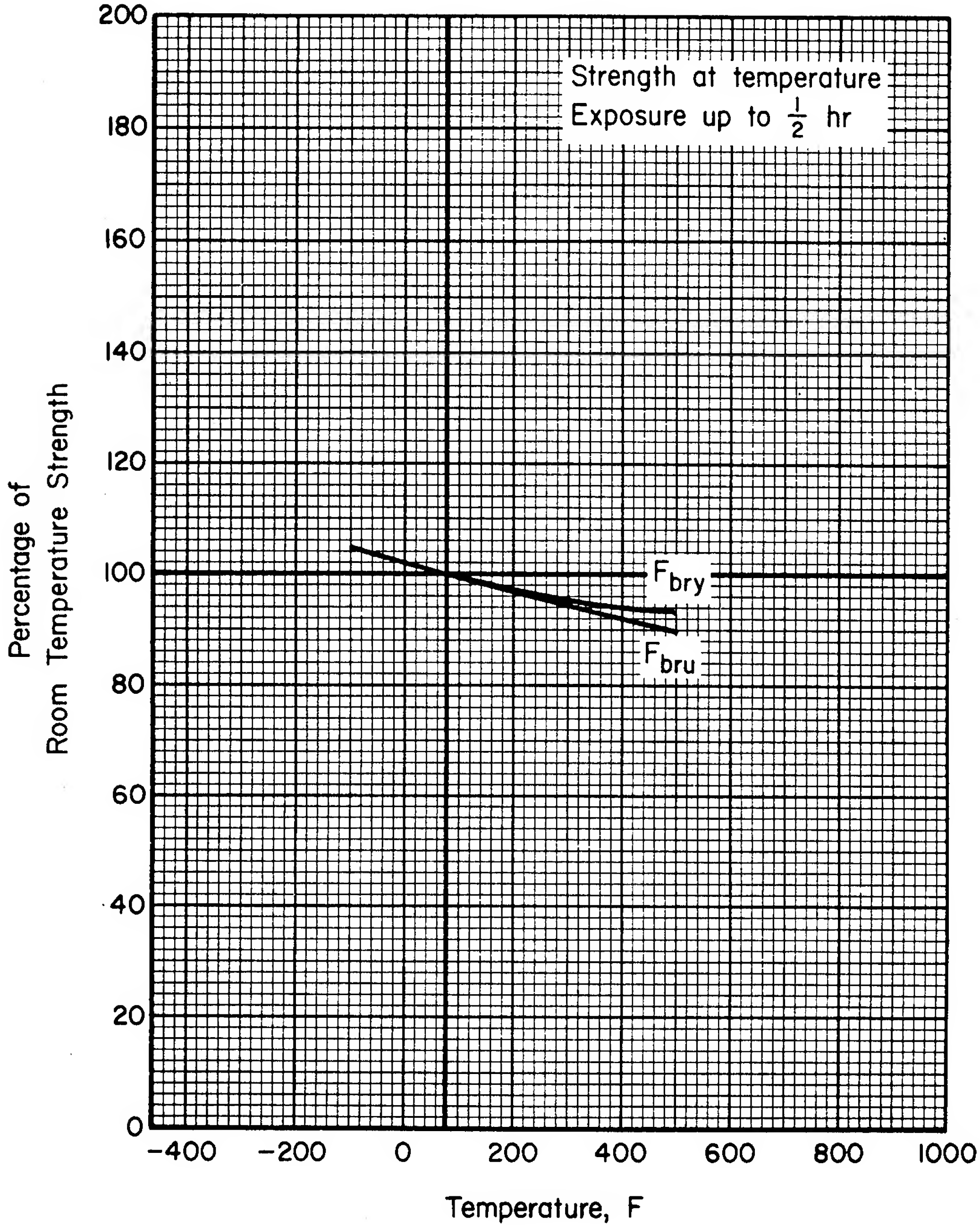

FIGURE 2.4.3.1.3. *Effect of temperature on the bearing ultimate strength (F_{bru}) and the bearing yield strength (F_{bry}) of 9Ni-4Co-.30C steel hand forging.*

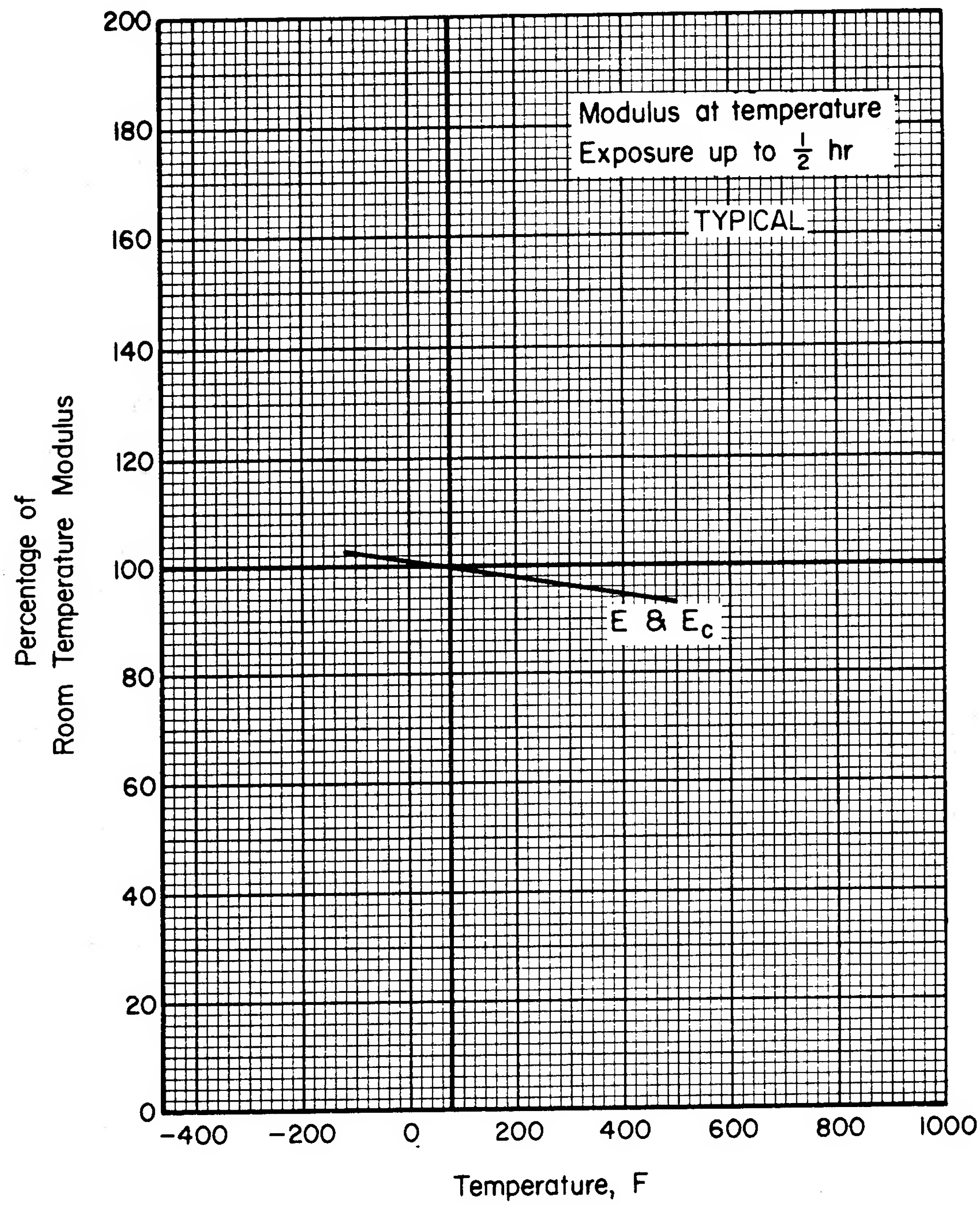

FIGURE 2.4.3.1.4. *Effect of temperature on the tensile and compressive moduli (E and E_c) of 9Ni-4Co-.30C steel.*

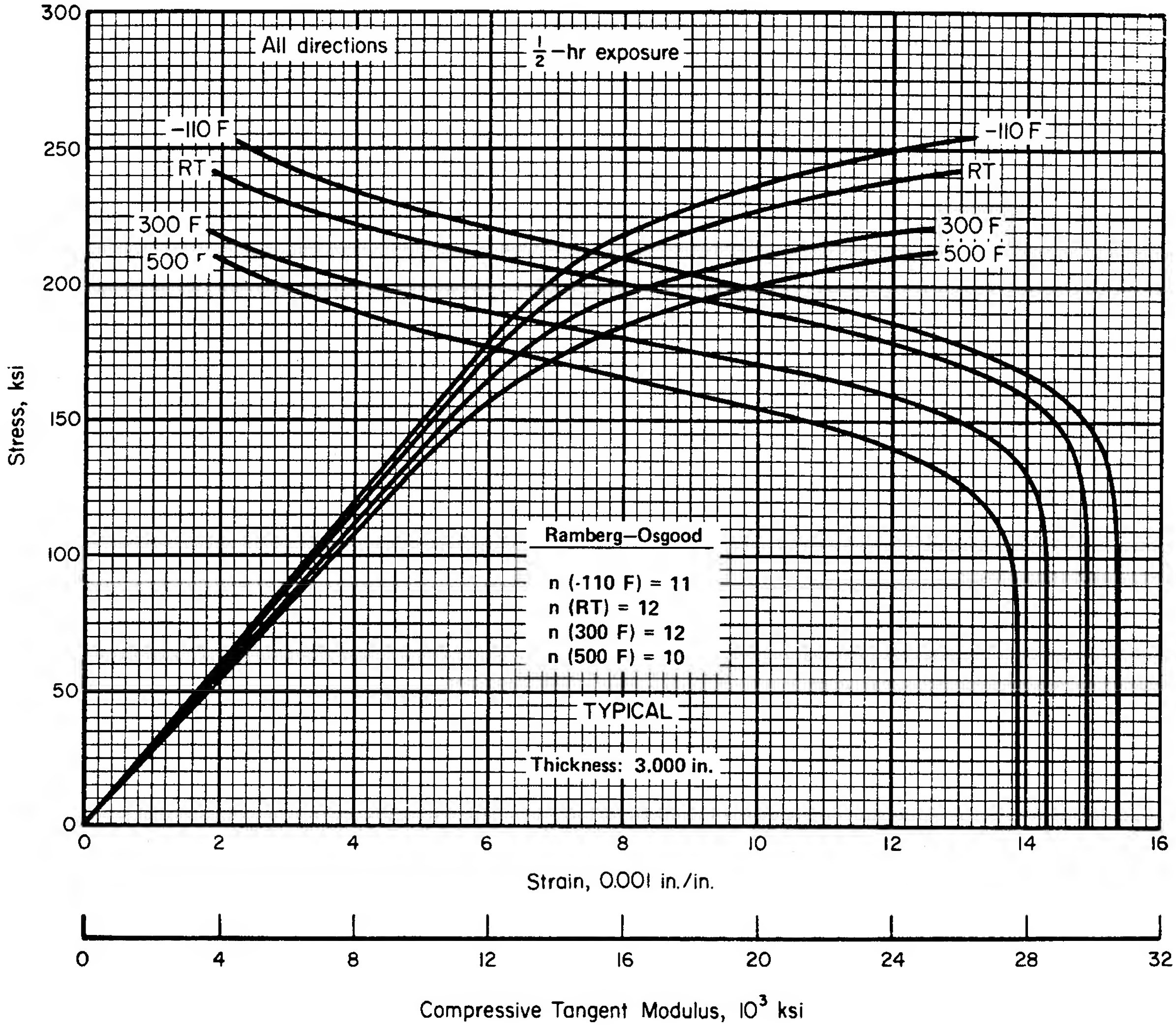

FIGURE 2.4.3.1.6(a). *Typical compressive stress-strain and compressive tangent-modulus curves for 9Ni-4Co-.30C steel hand forging at various temperatures.*

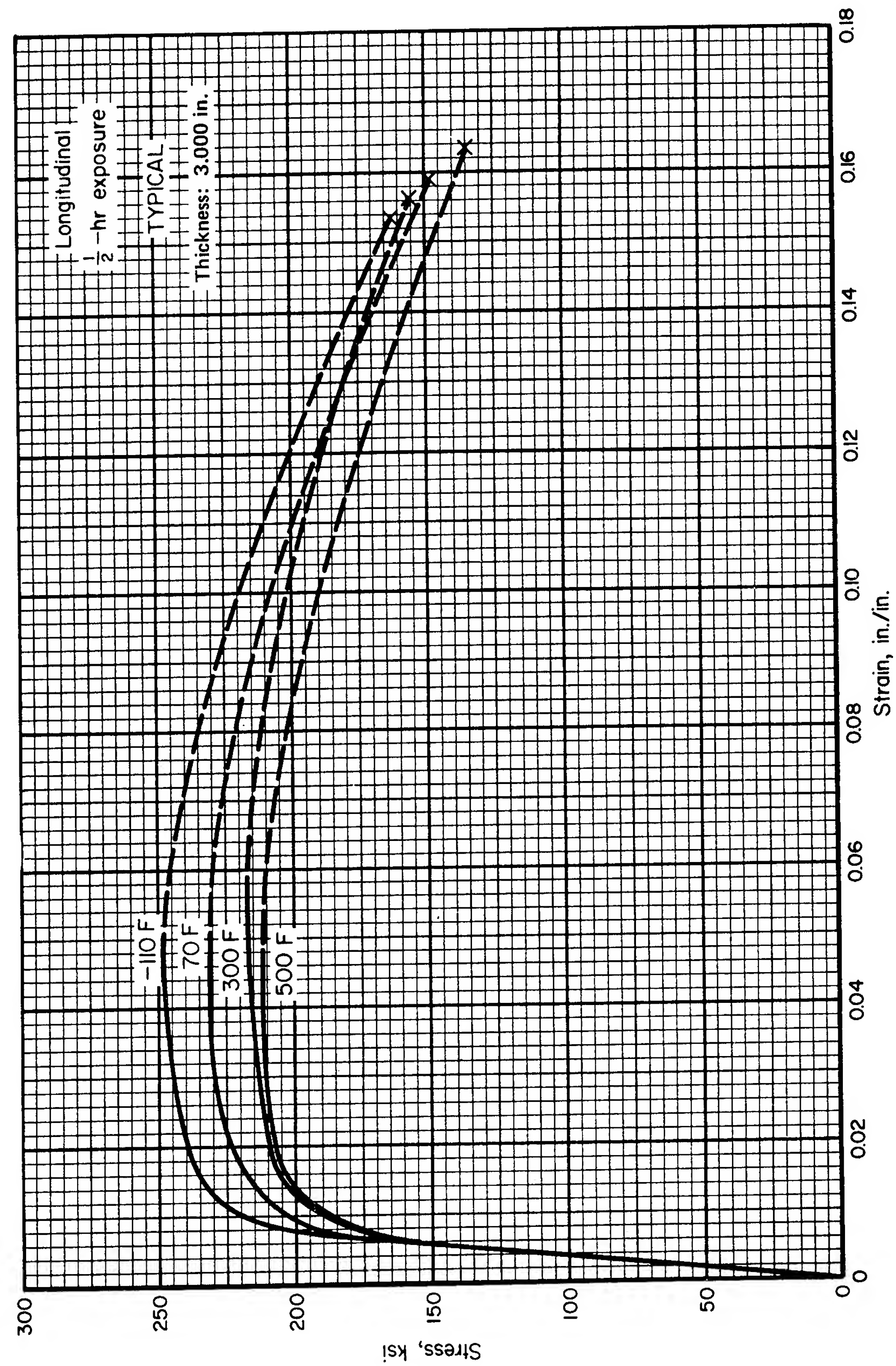

FIGURE 2.4.3.1.6(b). *Typical tensile stress-strain curves (full range) for 9Ni-4Co-.30C hand forging at various temperatures.*

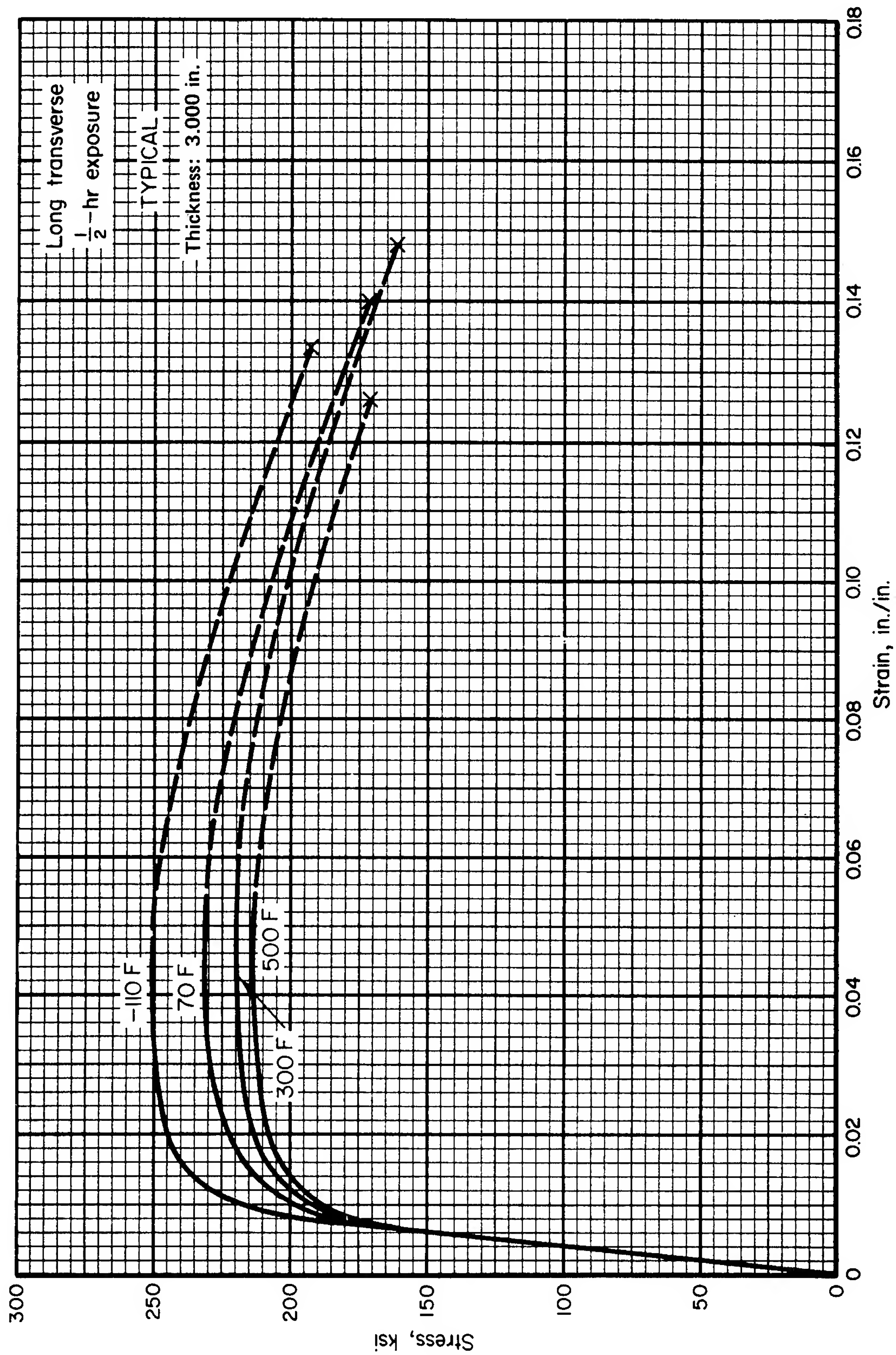

FIGURE 2.4.3.1.6(c). *Typical tensile stress-strain curves (full range) for 9Ni-4Co-.30C hand forging at various temperatures.*

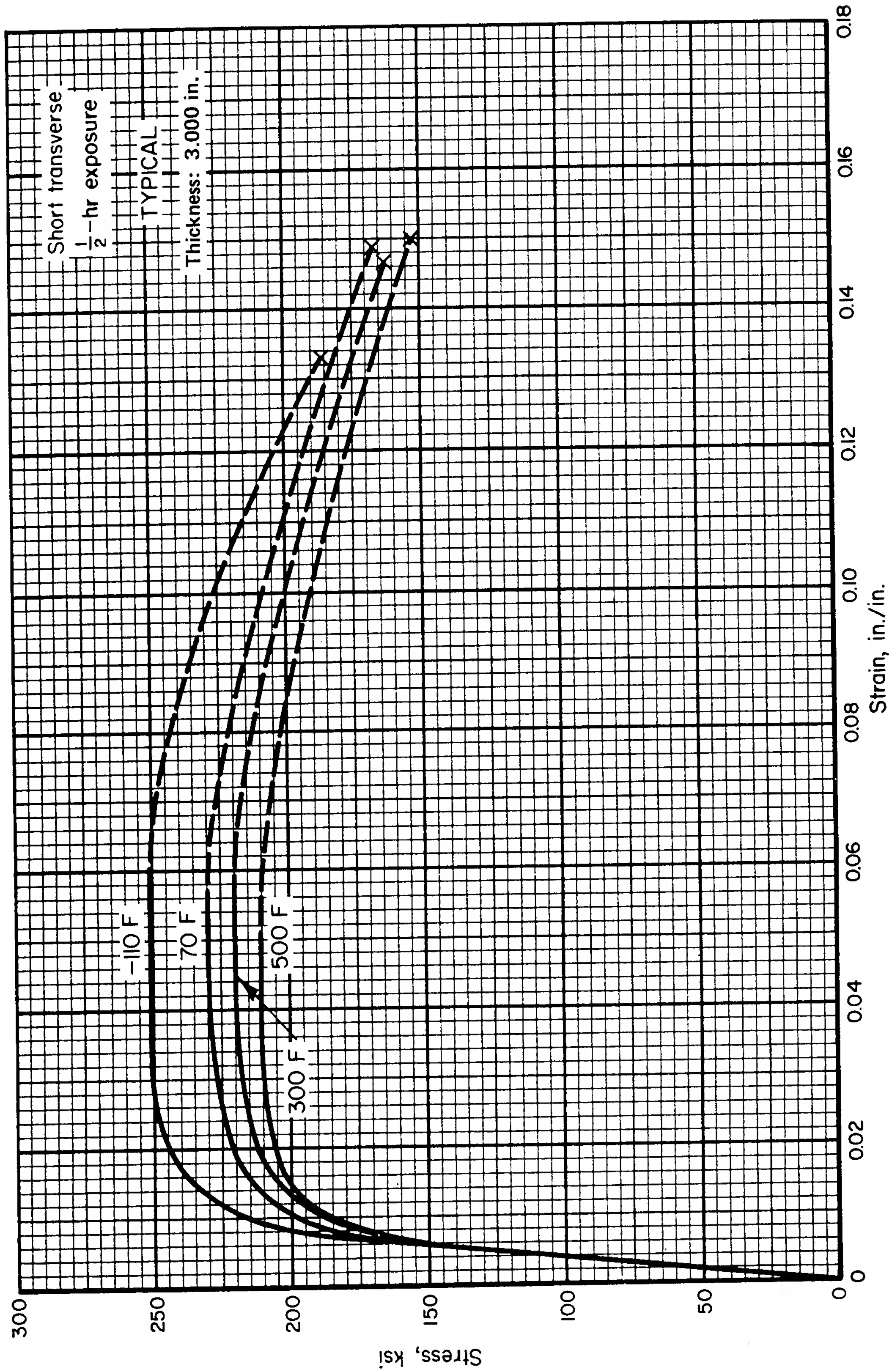

FIGURE 2.4.3.1.6(d). *Typical tensile stress-strain curves (full range) for 9Ni-4Co-.30C hand forging at various temperatures.*

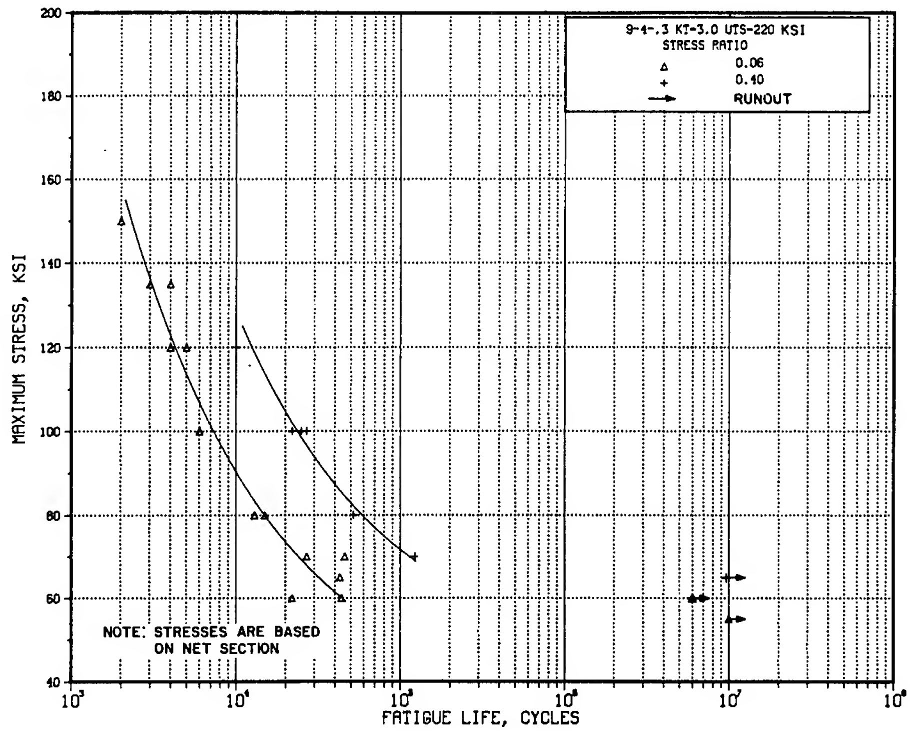

FIGURE 2.4.3.1.8. *Best-fit S/N curves for notched, K_t = 3.0, 9Ni-4Co-.30C steel hand forging, long and short transverse directions.*

Correlative Information for Figure 2.4.3.1.8

Product Form: Hand forging, 3 x 9 inch

Properties:	TUS, ksi	TYS, ksi	Temp., F
	231	197	RT (LT)

Specimen Details: Notched, V-Groove K_t = 3.0
0.354-inch gross diameter
0.250-inch net diameter
0.01-inch root radius
60° flank angle, ω

Surface Condition: Not specified

Reference: 2.4.3.1.8

Test Parameters:

Loading - Axial
Frequency - 1800 cpm
Temperature - RT
Environment - Air

No. of Heats/Lots: 3

Equivalent Stress Equation:

Log N_f = 7.77-2.15 log (S_{eq}-28.32)
$S_{eq} = S_{max} (1-R)^{0.79}$
Standard Error of Estimate = 0.12
Standard Deviation in Life = 0.47
R^2 = 93%

Sample Size = 22

[Caution: The equivalent stress model may provide unrealistic life predictions for stress ratios beyond those represented above]

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2.5 High-Alloy Steels

2.5.0 COMMENTS ON HIGH-ALLOY STEELS.—The high-alloy steels in this section are those steels that are substantially higher in alloy content than the intermediate alloy steels described in Section 2.4 but are not stainless steels. The 18 Ni maraging and AF1410 steels are in this category.

2.5.0.1 *Metallurgical Considerations.*—The 18 Ni maraging steels are iron base alloys with nominally 18 percent nickel, 7 to 9 percent cobalt, 3 to 5 percent molybdenum, less than 1 percent titanium, and very low carbon content, below 0.03 percent. Upon cooling from the annealing or hot-working temperature, these steels transform to a soft martensite which can be easily machined or formed. The steels can be subsequently aged (maraged) to high strengths by heating to a lower temperature, 900 F.

AF1410 is an iron base alloy with nominally 14 percent cobalt, 10 percent nickel, 2 percent chromium, 1 percent molybdenum, and 0.15 percent carbon. When quenched from austenitizing temperatures, AF1410 forms a highly dislocated lath martensitic structure with very little twinning or retained austenite. At aging temperatures ranging from 900 to 1000 F, a precipitation of extremely fine alloy carbide containing chromium and molybdenum occurs, which simultaneously develops strength and toughness properties.

2.5.1 18 Ni MARAGING STEELS

2.5.1.0 *Comments and Properties.*—The 250 and 280 (300) maraging steels are normally supplied in the annealed condition and are heat treated to high strengths, without quenching, by aging at 900 F. The steels are characterized by high hardenability and high strength combined with good toughness. The 250 and 280 (300) designation refers to the nominal yield strengths of the two alloys. The two alloys are available in the form of sheet, plate, bar, and die forgings. Only the consumable electrode-vacuum-melted quality grades are considered in this section.

Manufacturing Considerations.—The 250 and 280 grades are readily hot worked by conventional rolling and forging operations. These grades also have good cold forming characteristics in spite of the relatively high hardness in the annealed (martensitic) condition. The machinability of the 250 and 280 grades is not unlike 4330 steel at equivalent hardness. The 18 Ni maraging steels can be readily welded in either the annealed or aged conditions without preheating. Welding of aged material should be followed by aging at 900 F to strengthen the weld area.

Environmental Considerations.—Although the 18 Ni maraging steels are high in alloy content, these grades are not corrosion resistant. Since the general corrosion resistance is similar to the low-alloy steels, these steels require protective coatings. The 250 grade reportedly has better resistance to stress corrosion cracking than the low-alloy steels at the same strength.

Specifications and Properties.—Material specifications for these steels are shown in Table 2.5.1.0(a). The room temperature properties for material aged at 900 F are shown in Tables 2.5.1.0(b) and (c), and the effect of temperature on physical properties is shown in Figure 2.5.1.0.

TABLE 2.5.1.0(a). *Material Specifications for 18 Ni Maraging Steels*

Grade	Specification	Form
250	AMS 6520	Sheet and plate
250	AMS 6512	Bar
280 (300)	AMS 6521	Sheet and plate
280 (300)	AMS 6514	Bar

2.5.1.1 *Maraged Condition (aged at 900 F).*—Effect of temperature on 250 and 280 grade maraging steel is presented in Figures 2.5.1.1.1 through 2.5.1.1.4. Figures 2.5.1.1.6(a) and (b) are room and elevated temperature tensile stress-strain curves. Typical compressive stress-strain and tangent-modulus curves at room temperature are presented in Figures 2.5.1.1.6(c) and (d). Figure 2.5.1.1.6(e) is a full-range stress-strain curve at room temperature for 280 grade maraging steel.

TABLE 2.5.1.0(b). *Design Mechanical and Physical Properties of 250 Maraging Steel*

Specification	AMS 6520			AMS 6512	
Form	Sheet	Plate		Bar	
Condition	Maraged at 900 F			Maraged at 900 F	
Thickness or diameter, in	≤0.187	0.187-0.250	>0.250	<4.000	4.000-10.000
Basis	S	S	S	S	S
Mechanical Properties:					
F_{tu} ksi:					
L	247	252	...	255	245
T	255	255	255	255	245
F_{ty}, ksi:					
L	238	242	...	250	240
T	245	245	245	250	240
F_{cy}, ksi:					
L	221	...	...	260	...
T	225	255	...	...	...
F_{su}, ksi	148	155	...	148	...
F_{bru}, ksi:					
(e/D = 1.5)	327	352	...	...	...
(e/D = 2.0)	444	448	...	...	...
F_{bry}, ksi:					
(e/D = 1.5)	278	324	...	...	...
(e/D = 2.0)	353	354	...	...	...
e, percent:					
L	...	...	...	6	5
T	a	a	a	4	3
RA, percent:					
L	...	...	...	45	30
T	...	...	...	35	20
E, 10^3 ksi	26.5				
E_c, 10^3 ksi:					
L	28.2				
T	29.4				
G, 10^3 ksi	...				
μ	0.31				
Physical Properties:					
ω, lb/in.^{3}	0.286				
C, K, and α	See Figure 2.5.1.0				

[a] ≤0.090 2.5%
0.091-0.125 3.0%
0.126-0.250 4.0%
0.251-0.375 5.0%
≥0.376 6.0%

TABLE 2.5.1.0(c). *Design Mechanical and Physical Properties of 280 Maraging Steel*

Specification	AMS 6521			AMS 6514	
Form	Sheet	Plate		Bar	
Condition	Maraged at 900 F			Maraged at 900 F	
Thickness or diameter, in.	≤0.187	0.188-0.250	>0.250	<4.000	4.000-10.000
Basis	S	S	S	S	S
Mechanical Properties:					
F_{tu} ksi:					
L	271	276	...	280	275
T	280	280	280	280	275
F_{ty}, ksi:					
L	262	267	...	270	270
T	270	270	270	270	270
F_{cy}, ksi					
L	244	...	...	281	...
T	248	281	...	...	...
F_{su}, ksi	163	170	...	162	...
F_{bru}, ksi:					
(e/D = 1.5)	359	386	...	...	...
(e/D = 2.0)	487	492	...	...	...
F_{bry}, ksi:					
(e/D = 1.5)	306	357	...	...	...
(e/D = 2.0)	389	390	...	...	...
e, percent:					
L	...	...	...	5	4
T	a	a	a	4	2
RA, percent:					
L	...	...	...	30	25
T	...	...	...	25	20
E, 10^3 ksi	26.5				
E_c, 10^3 ksi:					
L	28.6				
T	29.6				
G, 10^3 ksi	...				
μ	0.31				
Physical Properties:					
ω, lb/in.^{3}	0.286				
C, K, and α	See Figure 2.5.1.0				

[a] ≤0.090 2.5%
0.091-0.125 3.0%
0.126-0.250 4.0%
0.251-0.375 5.0%
≥0.376 6.0%

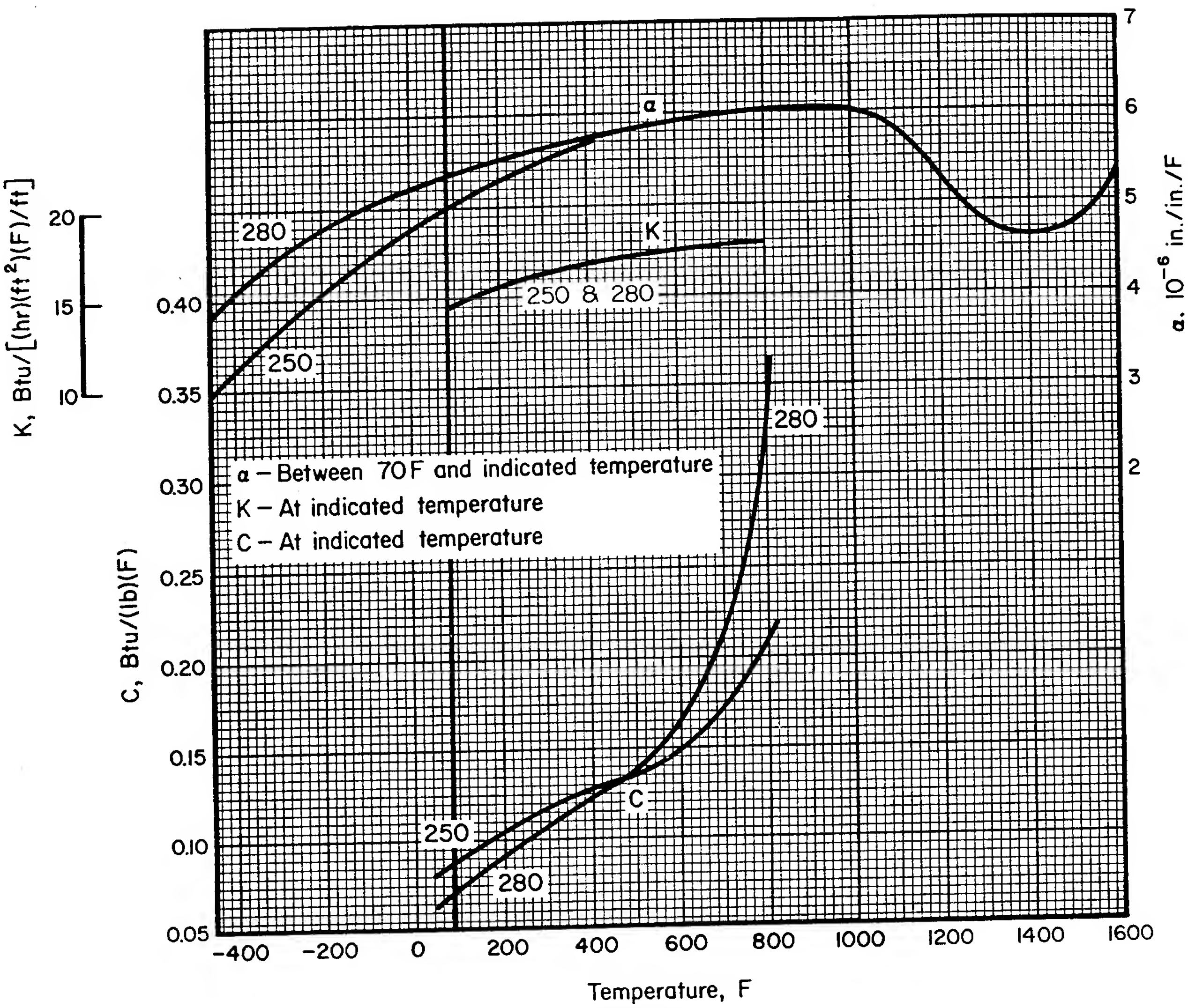

FIGURE 2.5.1.0. *Effect of temperature on the physical properties of 250 and 280 maraging steels.*

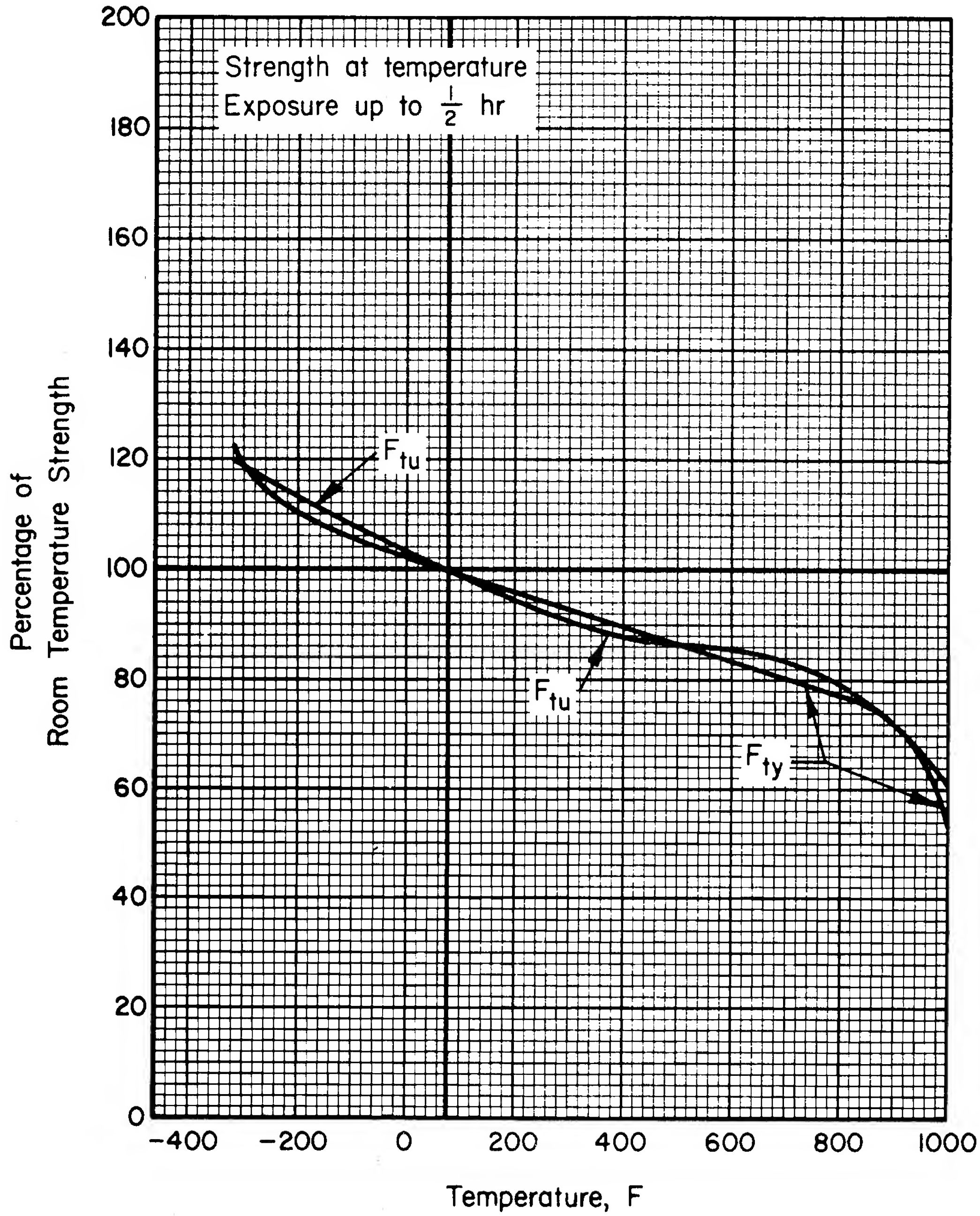

FIGURE 2.5.1.1.1. *Effect of temperature on the tensile ultimate strength (F_{tu}) and the tensile yield strength (F_{ty}) of 250 and 280 maraging steel sheet and plate.*

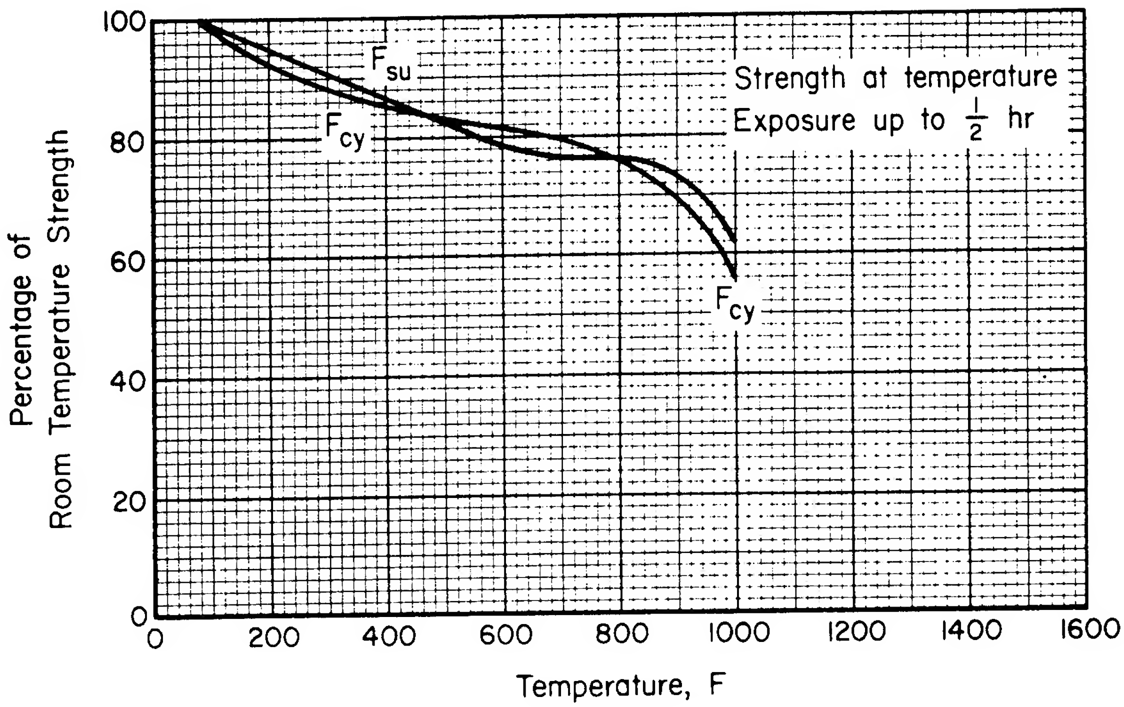

FIGURE 2.5.1.1.2. *Effect of temperature on the compressive yield strength (F_{cy}) and the shear ultimate strength (F_{su}) of 250 and 280 maraging steel sheet and plate.*

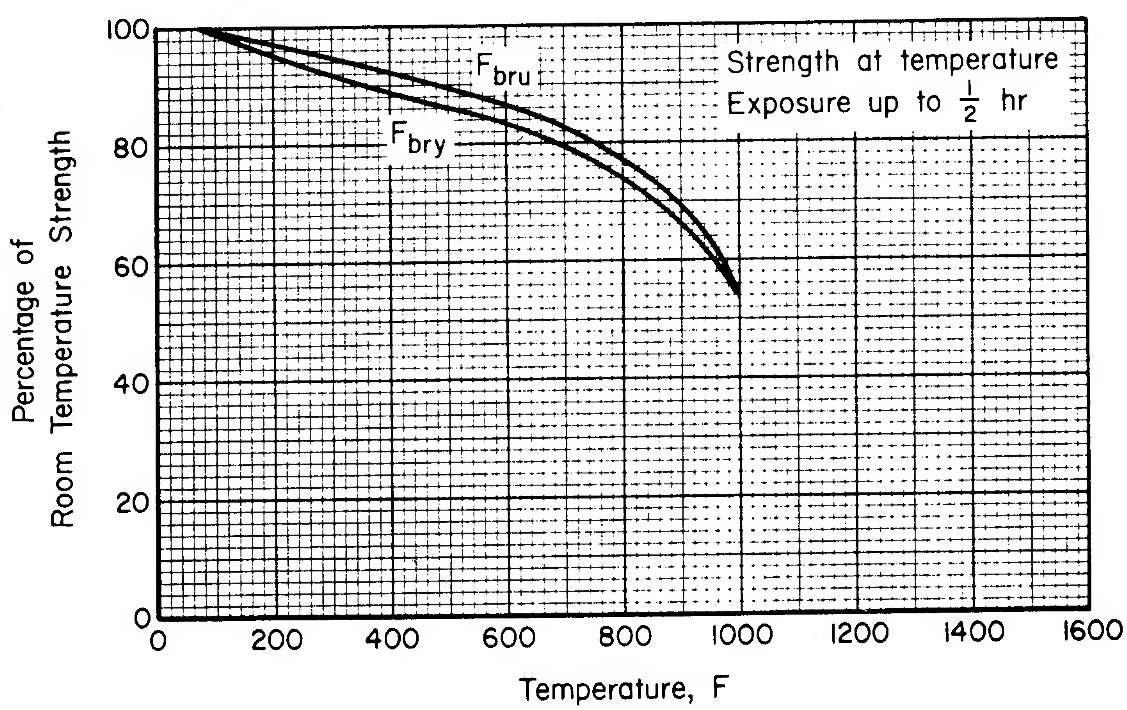

FIGURE 2.5.1.1.3. *Effect of temperature on the bearing ultimate strength (F_{bru}) and the bearing yield strength (F_{bry}) of 250 and 280 maraging steel sheet and plate.*

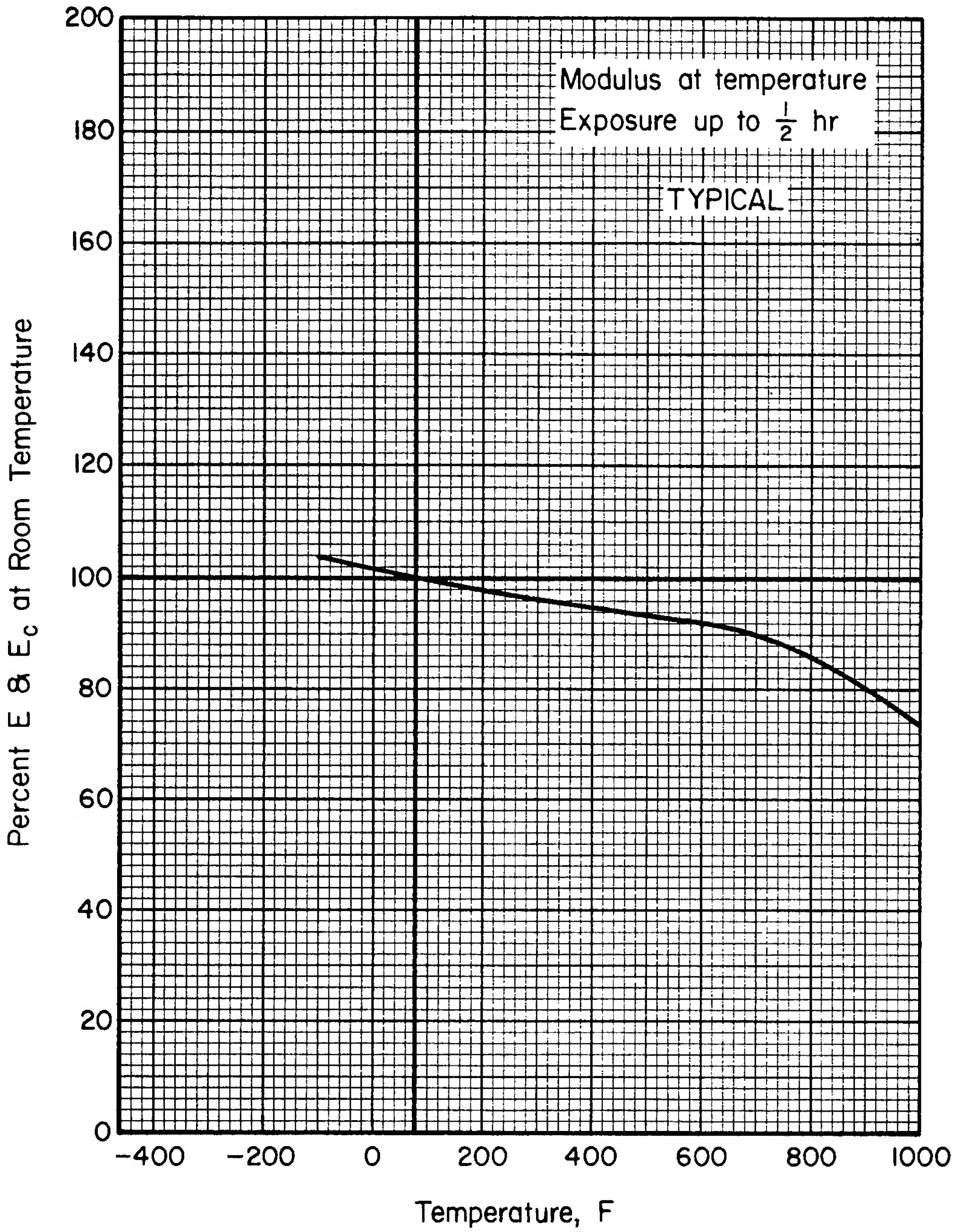

FIGURE 2.5.1.1.4. *Effect of temperature on the tensile and compressive moduli (E and E_c) of 250 and 280 maraging steel.*

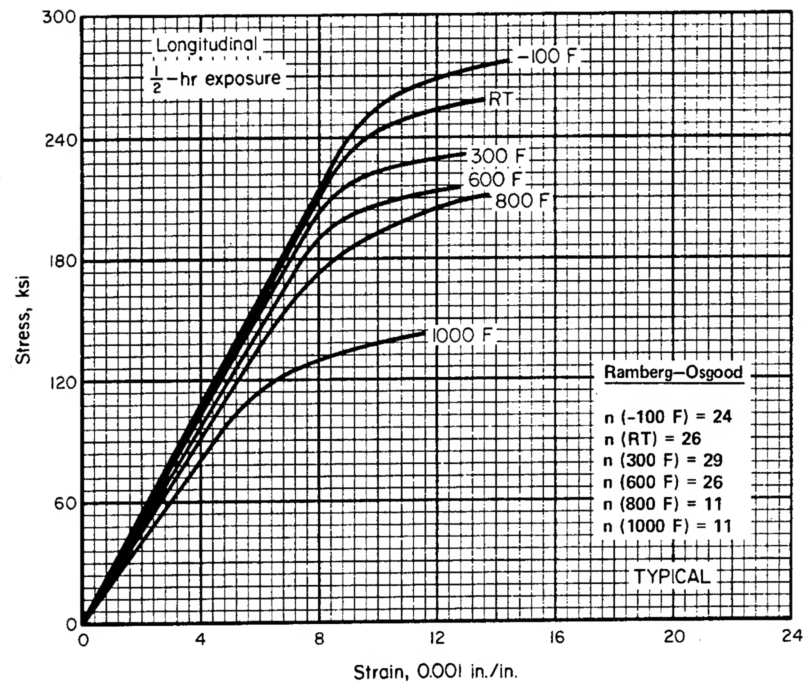

FIGURE 2.5.1.1.6(a). *Typical tensile stress-strain curves at room and elevated temperatures for 250 maraging steel bar.*

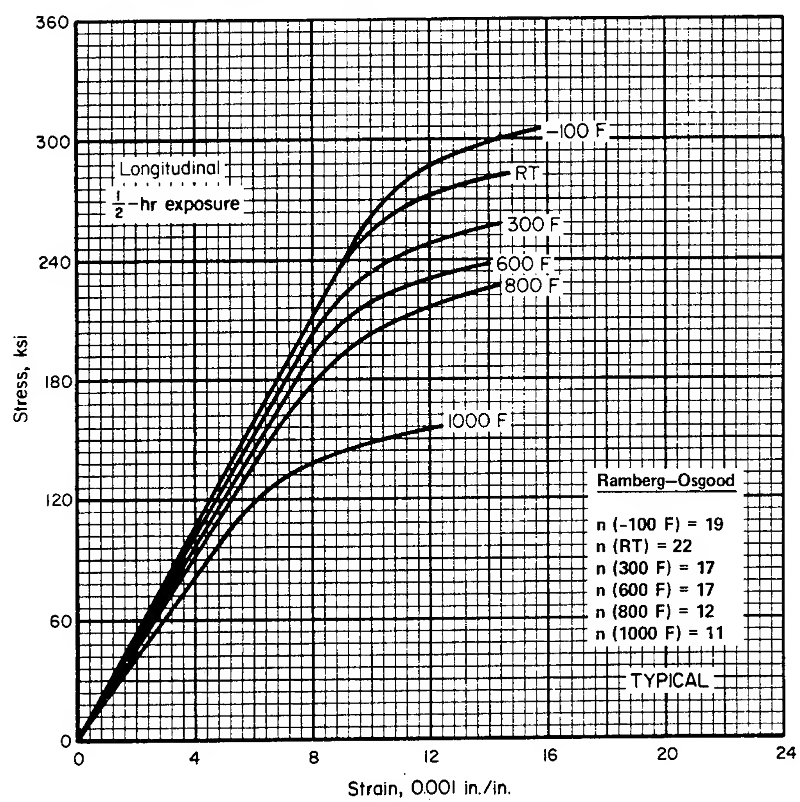

FIGURE 2.5.1.1.6(b). *Typical tensile stress-strain curves at room and elevated temperatures for 280 maraging steel bar.*

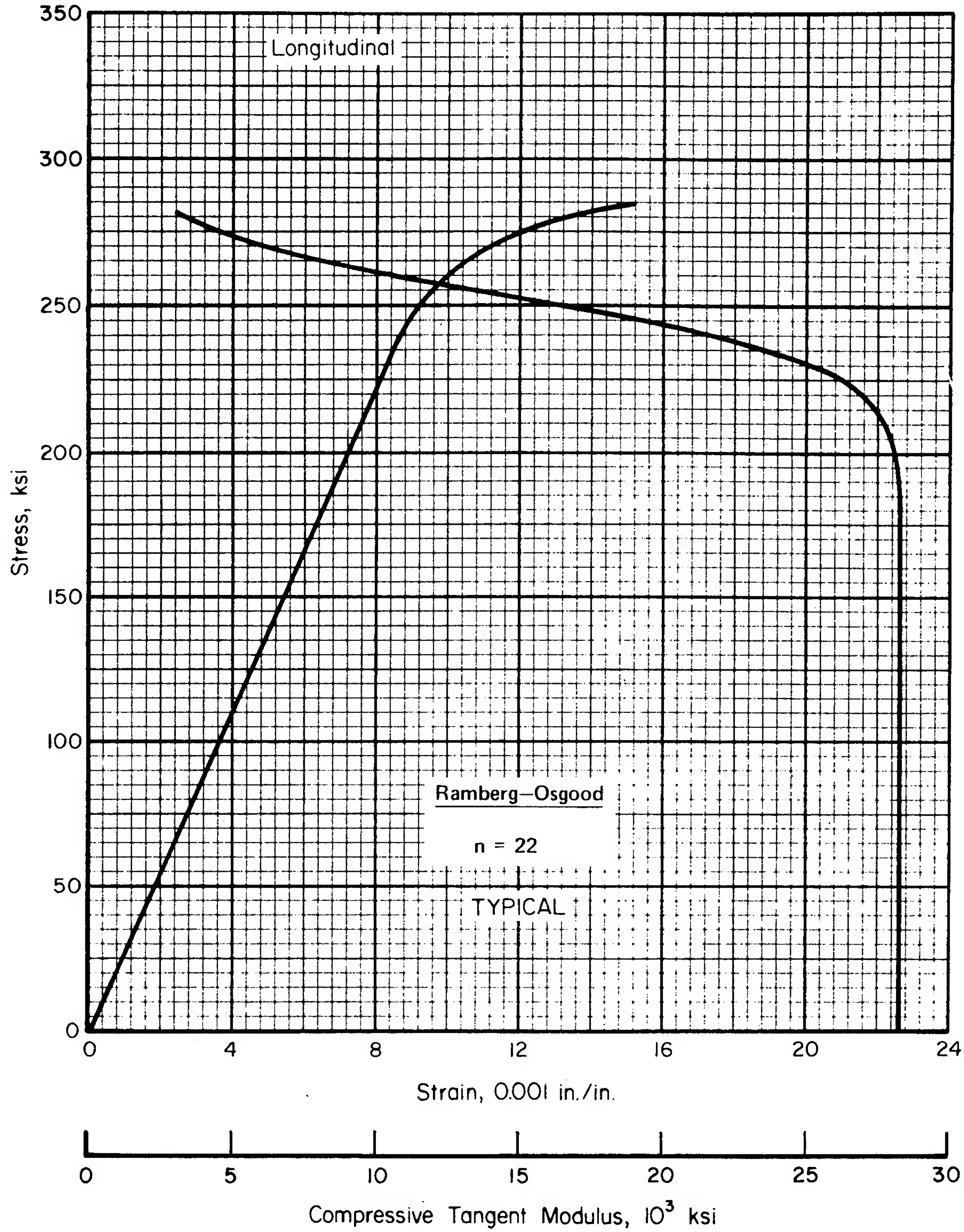

FIGURE 2.5.1.1.6(c). *Typical compressive stress-strain and compressive tangent-modulus curves for 250 maraging steel bar at room temperature.*

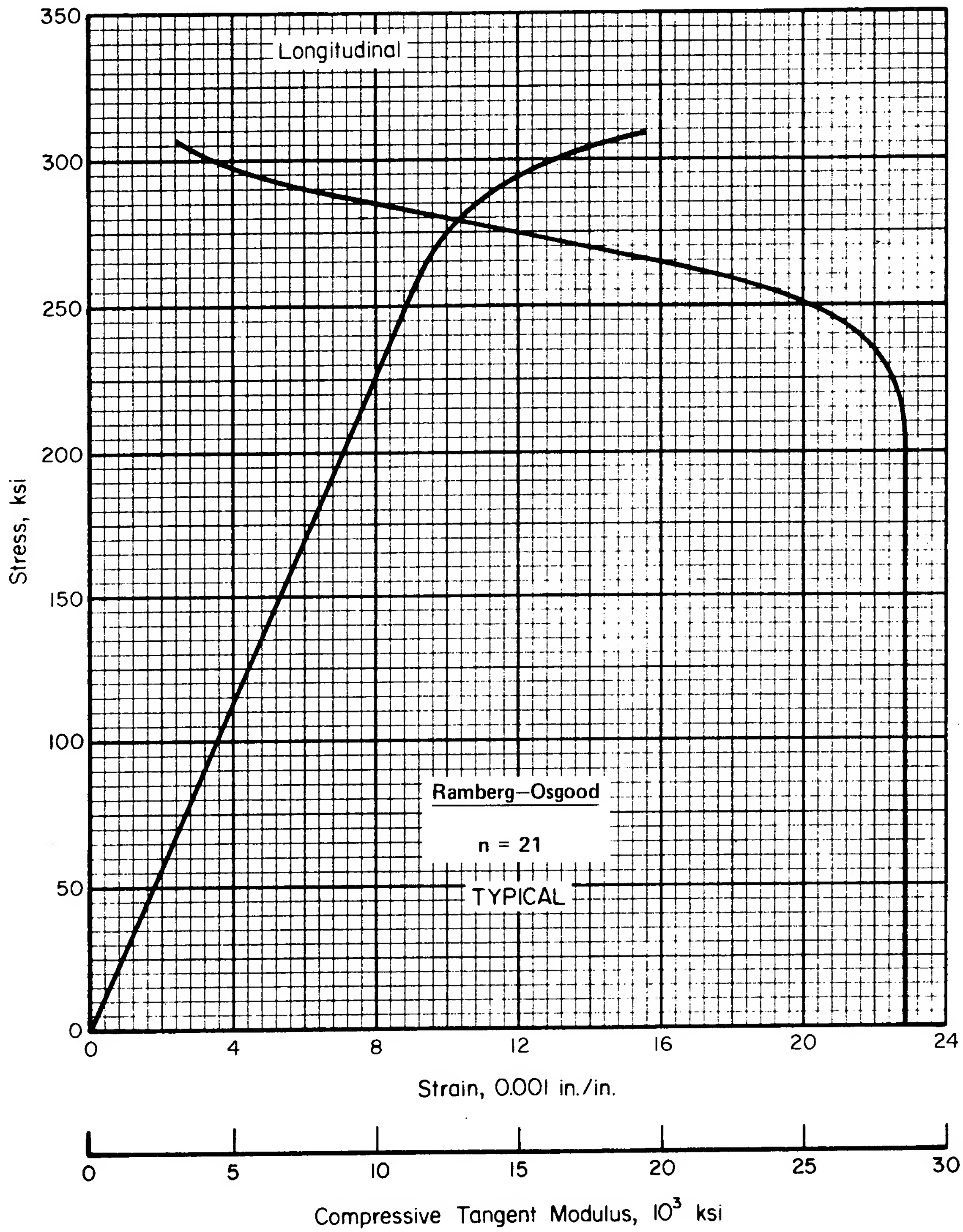

FIGURE 2.5.1.1.6(d). *Typical compressive stress-strain and compressive tangent-modulus curves for 280 maraging steel bar at room temperature.*

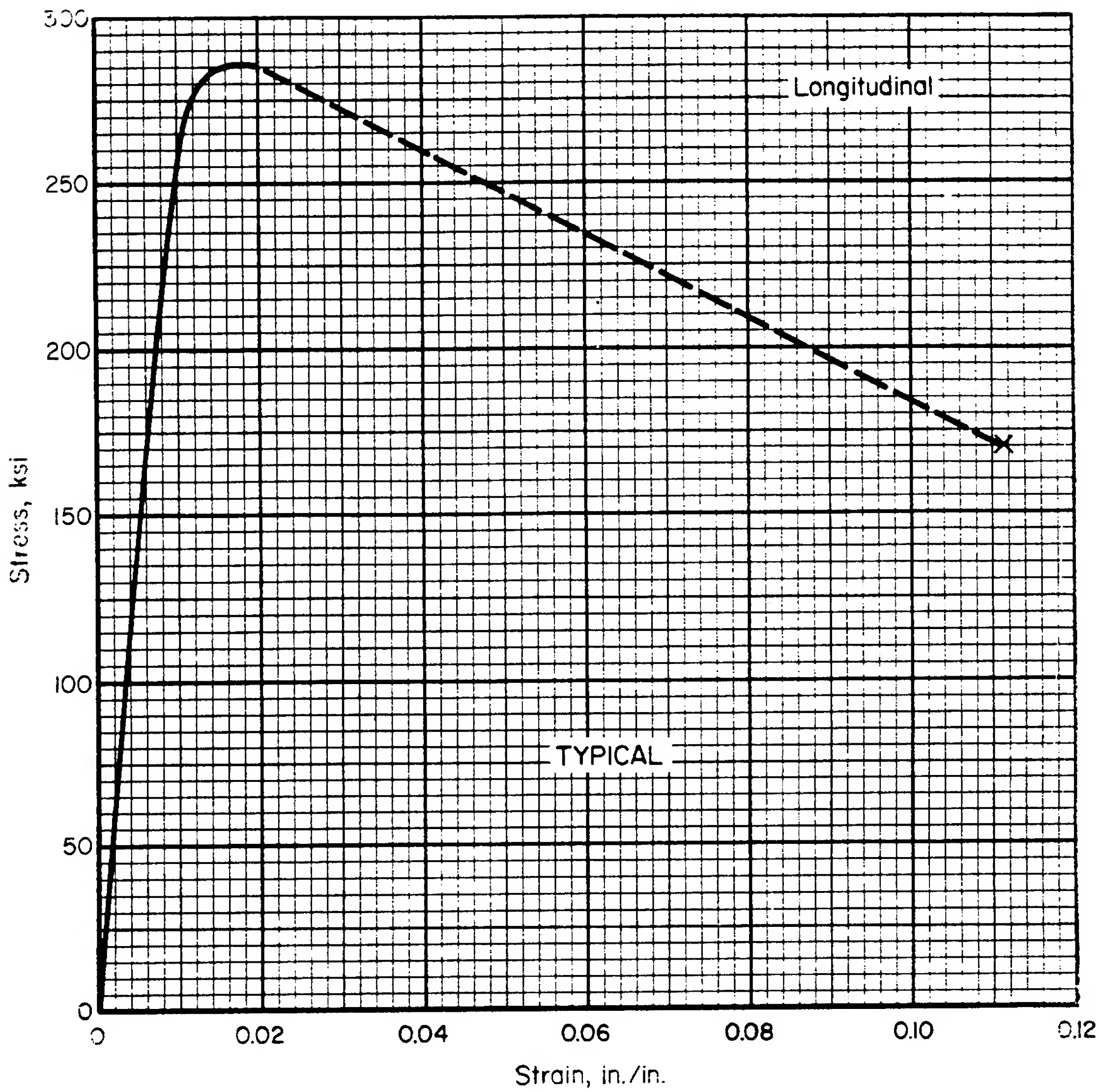

FIGURE 2.5.1.1.6(e). *Typical tensile stress-strain curve (full range) for 280 maraging steel bar at room temperature.*

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2.5.2 AF1410

2.5.2.0 *Comments and Properties.*—AF1410 alloy was developed specifically to have high strength, excellent fracture toughness, and excellent weldability when heat treated to 235 to 255 ksi ultimate tensile strength. AF1410 has good weldability and does not require preheating prior to welding. The alloy maintains good toughness at cryogenic temperatures, as well as high strength and stability at temperatures up to 800 F. The alloy is available in a wide variety of sizes and forms, including billet, bar, plate, and die forgings. The alloy is produced by vacuum induction melting followed by vacuum remelting.

Heat Treatment.—The heat treatment for this alloy consists of heating to 1650 ± 25 F for 1 hour, forced-air cooling to room temperature, reheating to 1525 ± 25 F for 1 hour, forced-air cooling to room temperature, cooling to -100 ± 15 F, holding at temperature for 1 hour, warming to room temperature, and aging at 950 ± 10 F for 5 hours, and air cooling. A forced-air cool from austenitizing temperatures should be used for section thicknesses up to 2 inches. For sections of greater thickness, an oil quench should be utilized. A single austenitizing treatment (1525 ± 25 F) can be used to minimize heat treating distortion with a resulting slight decrease in fracture toughness.

Environmental Considerations.—AF1410 has general corrosion resistance similar to the maraging steels. It should not be used in the unprotected condition. The alloy is highly resistant to stress corrosion cracking compared to other high strength steels.

Specification and Properties.—A material specification for AF1410 is presented in Table 2.5.2.0(a). Room temperature mechanical properties are shown in Table 2.5.2.0(b).

TABLE 2.5.2.0(a). *Material Specification for AF1410 Steel*

Specification	Form
AMS 6527	Bar and forging

2.5.2.1 *Heat-Treated Condition.*—Typical stress-strain curves at room temperature are shown in Figures 2.5.2.1.6(a) and (b).

TABLE 2.5.2.0(b). *Design Mechanical and Physical Properties of AF1410 Steel Bar*

Specification	AMS 6527
Form	Bar
Condition	a
Cross-sectional area, sq. in.	≤100[b]
Thickness or diameter, in.	≤4.25[b]
Basis	S
Mechanical Properties:	
F_{tu}, ksi:	
L	235
LT[c]	235
ST[c]	235
F_{ty}, ksi:	
L	215
LT[c]	215
ST[c]	215
F_{cy}, ksi:	
L	223
ST[c]	225
F_{su}, ksi	141
F_{bru}, ksi:	
(e/D = 1.5)	334
(e/D = 2.0)	435
F_{bry}, ksi:	
(e/D = 1.5)	269
(e/D = 2.0)	300
e, percent:	
L	12
LT[c]	12
ST[c]	12
RA, percent:	
L	60
LT[c]	55
ST[c]	55
E, 10^3 ksi	29.4
E_c, 10^3 ksi	30.9
G, 10^3 ksi	...
μ	...
Physical Properties:	
ω, lb/in.^{3}	0.283
C, K, and α	...

[a]Heat at 1650 ±25 F for one hour, forced-air cool to room temperature, heat at 1525 ±25 F for one hour, forced-air cool to room temperature, cool at -100 ±15 F for one hour, age at 950 ± 10 F for 5 hours, and air cool.
[b]Maximum size from which test specimens were rough machined prior to heat treatment.
[c]Applicable providing LT or ST dimension is ≥2.500 inches.

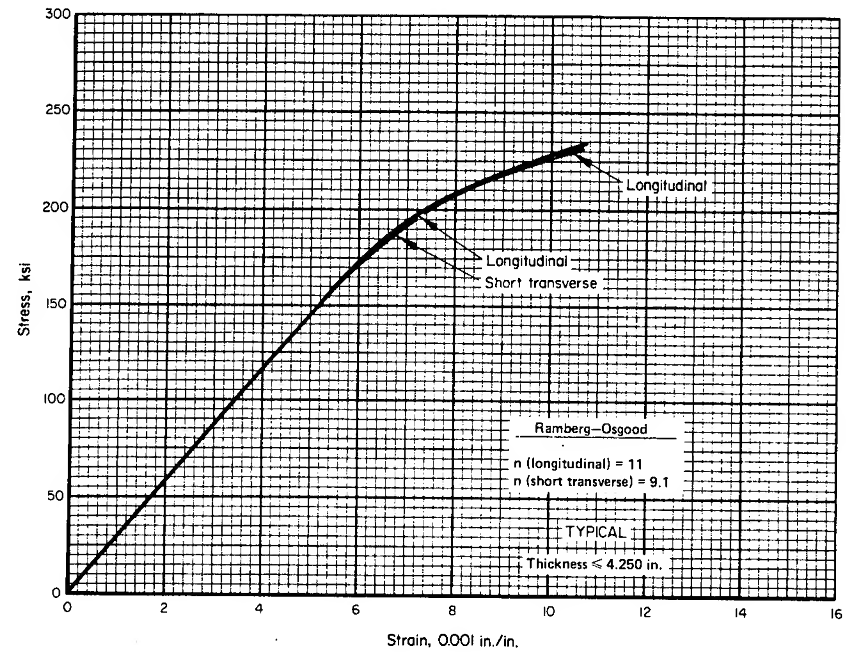

FIGURE 2.5.2.1.6(a). *Typical tensile stress-strain curves at room temperature for heat treated AF1410 steel bar.*

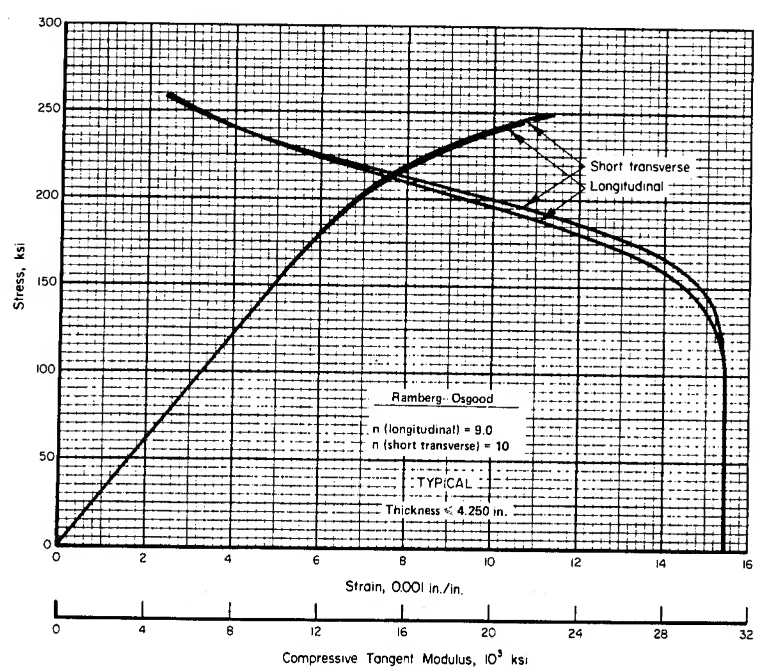

FIGURE 2.5.2.1.6(b). *Typical compressive stress-strain and compressive tangent-modulus curves at room temperature for heat-treated AF1410 steel bar.*

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2.5.3 AERMET 100

2.5.3.0 *Comments and Properties.*—AerMet 100 is a higher strength derivative of AF1410. The Ni-Co-Fe alloy can be heat treated to 280-300 ksi or to 290-310 ksi tensile strength while exhibiting excellent fracture toughness and high resistance to stress-corrosion cracking. AerMet 100 has good weldability and does not require preheating prior to welding. AerMet 100 is available in a wide variety of sizes and forms including billet, bar, sheet, strip, plate, wire, and die forgings. The alloy is produced by vacuum induction melting followed by vacuum-arc remelting.

Heat Treatment.—The heat treatment for this alloy consists of heating to 1625 ± 25 F, holding for 60 + 15, -0 minutes, cooling to -100 ± 15 F, holding for 60 ± 5 minutes, warming in air to room temperature. Parts over 1.25 inches in thickness shall be oil quenched from 1625 F. Parts ≤1.25 inches in thickness may be cooled in air from 1625 F. To achieve the 280-300 ksi tensile strength, aging is conducted at 900 ± 10°F for 5 to 8 hours and subsequently cooled in air. To achieve the 290-310 ksi tensile strength, aging is conducted at 875 ± 10°F for 5 to 8 hours and subsequently cooled in air.

Environmental Considerations.—AerMet 100 is not considered corrosion resistant; consequently, parts should be protected with a corrosion resistant coating. The alloy is highly resistant to stress corrosion cracking compared to other high strength steels of the same strength level.

This alloy displays good toughness at cryogenic temperatures as well as high strength and stability at temperatures up to 800 F.

Specification and Properties.—A material specification for AerMet 100 is shown in Table 2.5.3.0(a). Room temperature mechanical properties are presented in Table 2.5.3.0(b) for both heat treated conditions.

TABLE 2.5.3.0(a). *Material Specification for AerMet 100 Steel*

Specification	Form
AMS 6532	Bar and forging
AMS 6478	Bar and forging

2.5.3.1 *280-300 ksi Heat-Treated Condition.*—Typical stress-strain curves at room temperature are shown in Figures 2.5.3.1.6(a) and (b). A full-range tensile stress-strain curve is presented in Figure 2.5.3.1.6(c).

2.5.3.2 *290-310 ksi Heat-Treated Condition.*—Typical tensile and compression stress-strain curves and compression tangent modulus curves at room temperature are shown in Figures 2.5.3.2.6(a) and (b). A full-range tensile stress-strain curve is presented in Figure 2.5.3.2.6(c).

TABLE 2.5.3.0(b). *Design Mechanical and Physical Properties of AerMet 100 Steel Bar*

Specification	AMS 6532	AMS 6478
Form	Bar and Forging	
Condition	Solution treated and aged	
Cross-sectional area, in.^{2}.	≤ 100	
Thickness or diameter, in.	≤ 10.000	
Basis	S	S
Mechanical Properties:		
F_{tu}, ksi:		
L	280	290
LT[a]	280	290
ST[a]	280	290
F_{ty}, ksi:		
L	235	245
LT[a]	235	245
ST[a]	235	245
F_{cy}, ksi:		
L	262	281
ST[a]	263	279
F_{su}, ksi	175	182
F_{bru}[b], ksi:		
(e/D = 1.5)	433	448
(e/D = 2.0)	571	581
F_{bry}[b], ksi:		
(e/D = 1.5)	361	378
(e/D = 2.0)	411	442
e, percent:		
L	10	10
LT[a]	8	8
ST[a]	8	8
RA, percent:		
L	55	50
LT[a]	45	35
ST[a]	45	35
E, 10^3 ksi	28.0	
E_c, 10^3 ksi	28.1	
G, 10^3 ksi	...	
μ	...	
Physical Properties:		
ω, lb/in.^{3}	0.285	
C, K, and α	...	

[a]Applicable providing LT or ST dimension is ≤2.500 inches.
[b]Bearing values are "dry pin" values per Section 1.4.7.1.

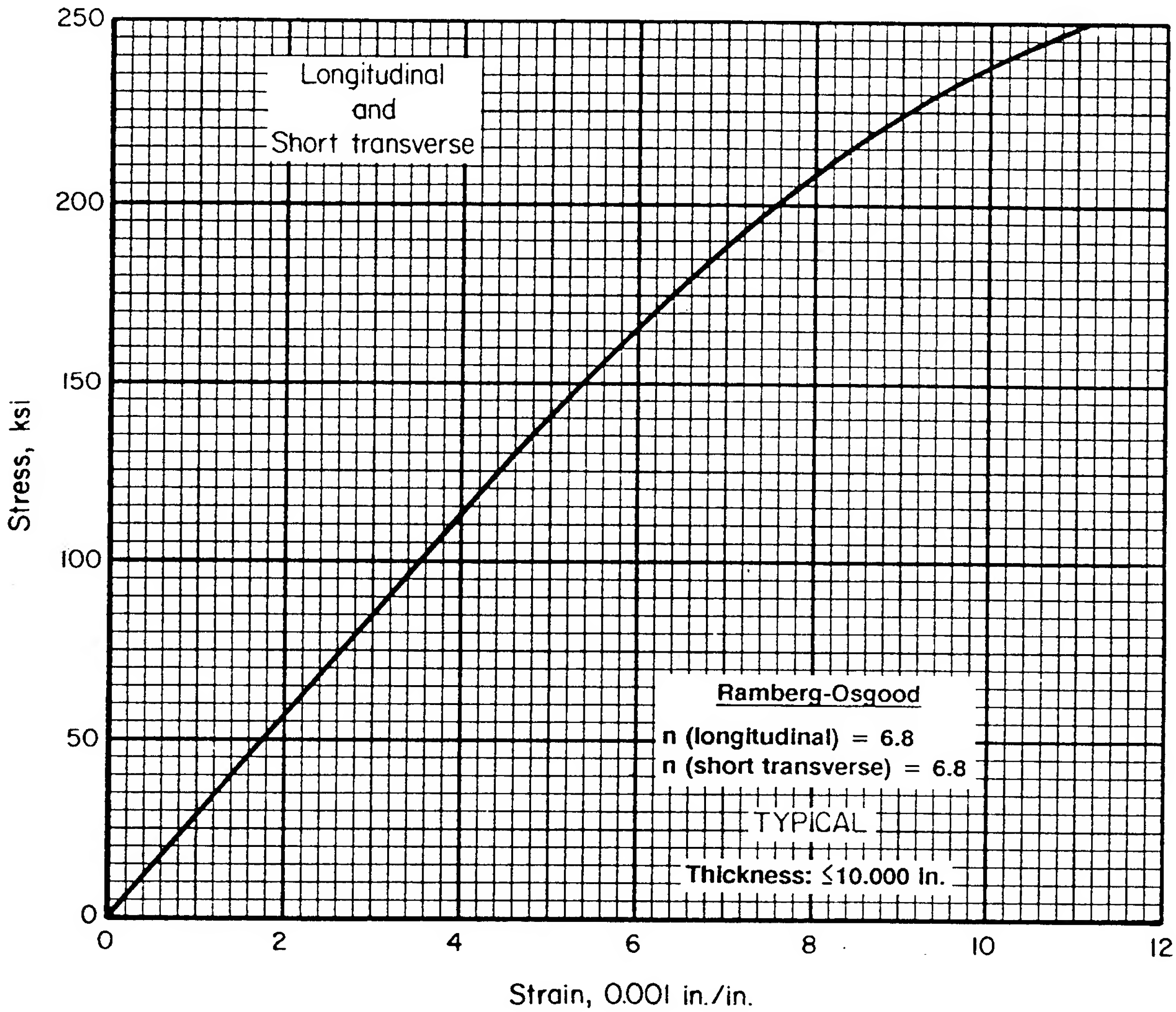

FIGURE 2.5.3.1.6(a). *Typical tensile stress-strain curve at room temperature for AerMet 100 steel bar, heat treated to 280-300 ksi.*

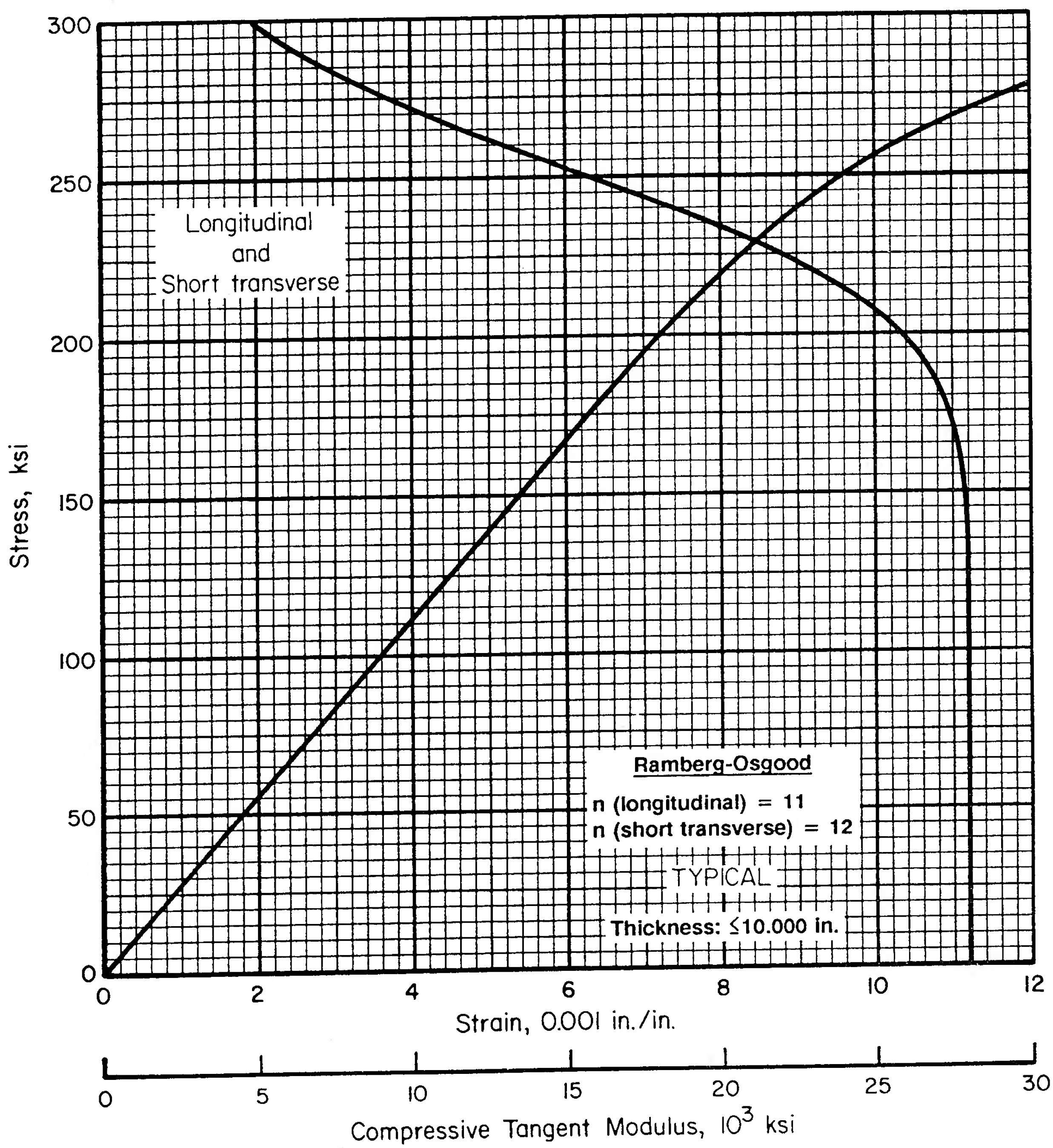

FIGURE 2.5.3.1.6(b). *Typical compressive stress-strain and compressive tangent-modulus curves at room temperature for AerMet 100 steel bar, heat treated to 280-300 ksi.*

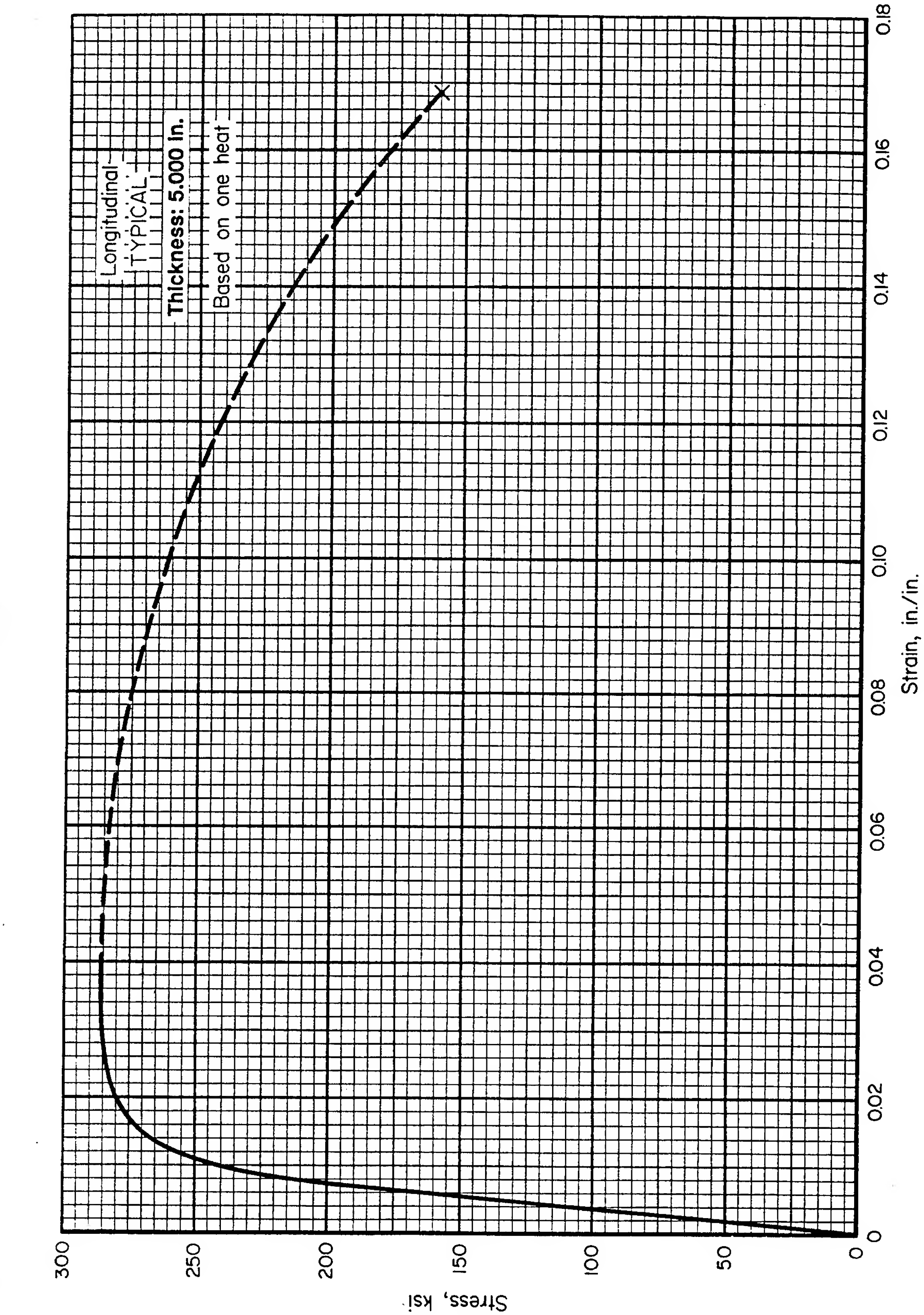

FIGURE 2.5.3.1.6(c). *Typical tensile stress-strain curve (full-range) at room temperature for AerMet 100 steel bar, heat treated to 280-300 ksi.*

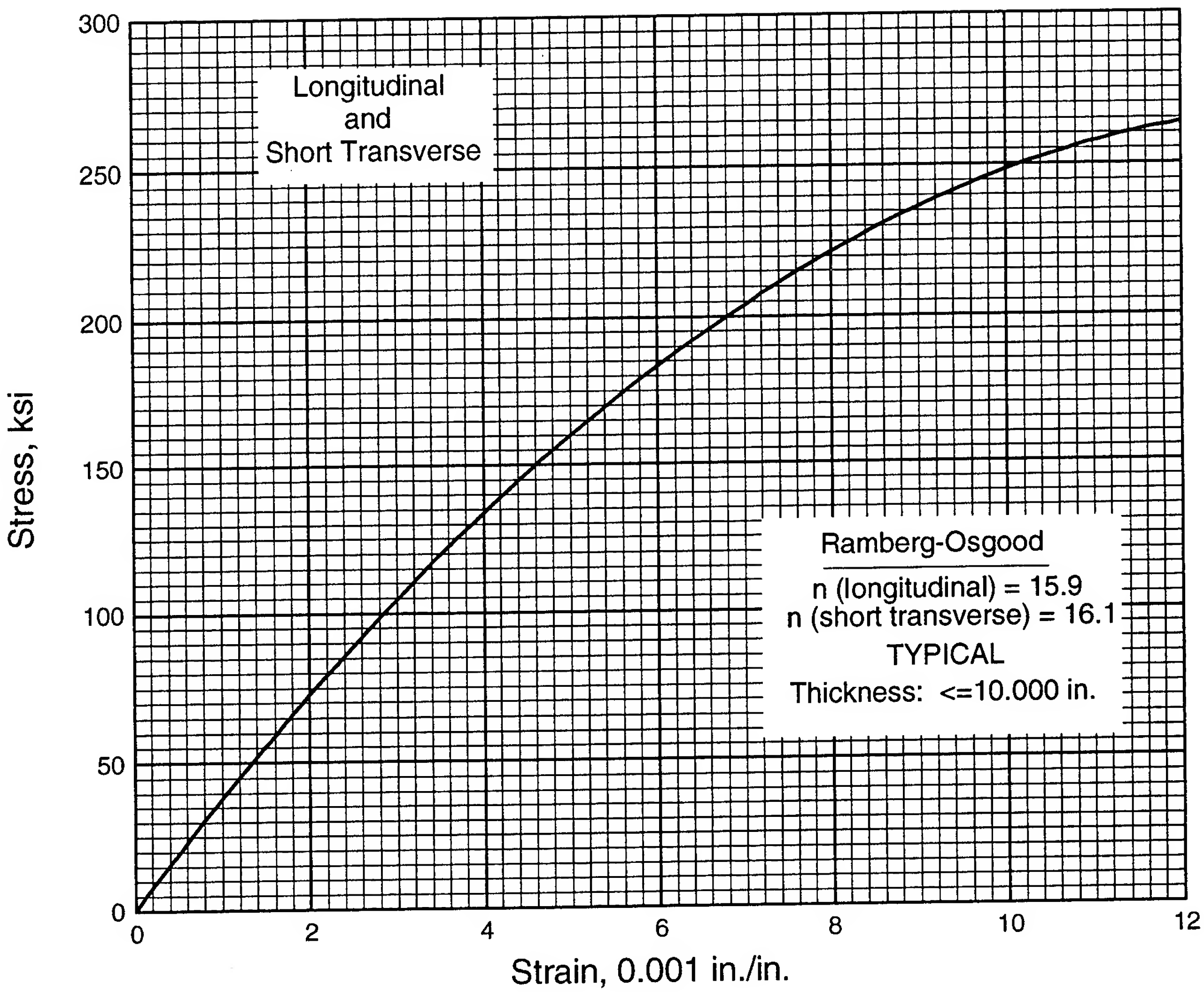

FIGURE 2.5.3.2.6(a). *Typical tensile stress-strain curve at room temperature for AerMet 100 steel bar, heat treated to 290-310 ksi.*

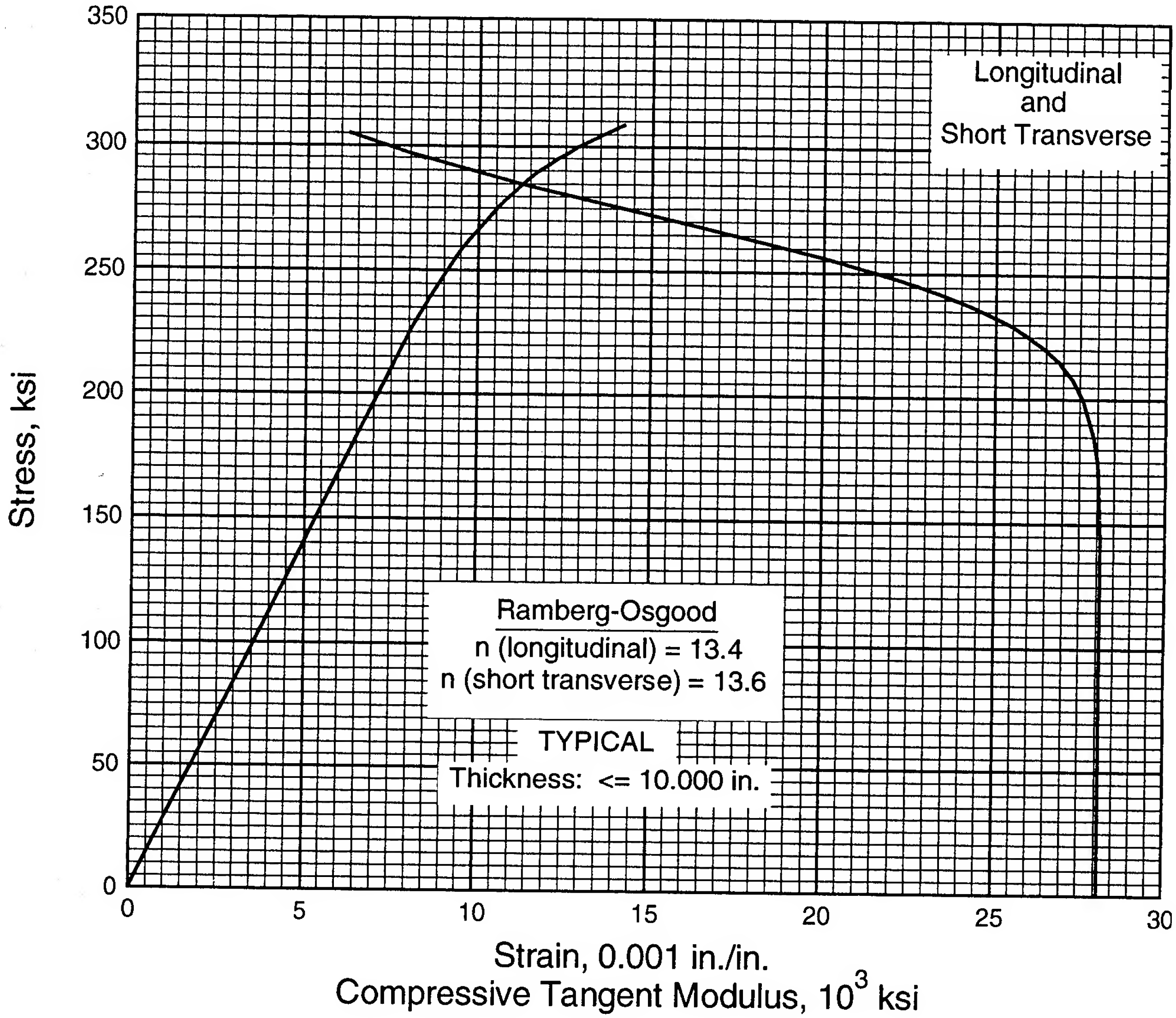

FIGURE 2.5.3.2.6(b). *Typical compressive stress-strain and compressive tangent-modulus curves at room temperature for AerMet 100 steel bar, heat treated to 290-310 ksi.*

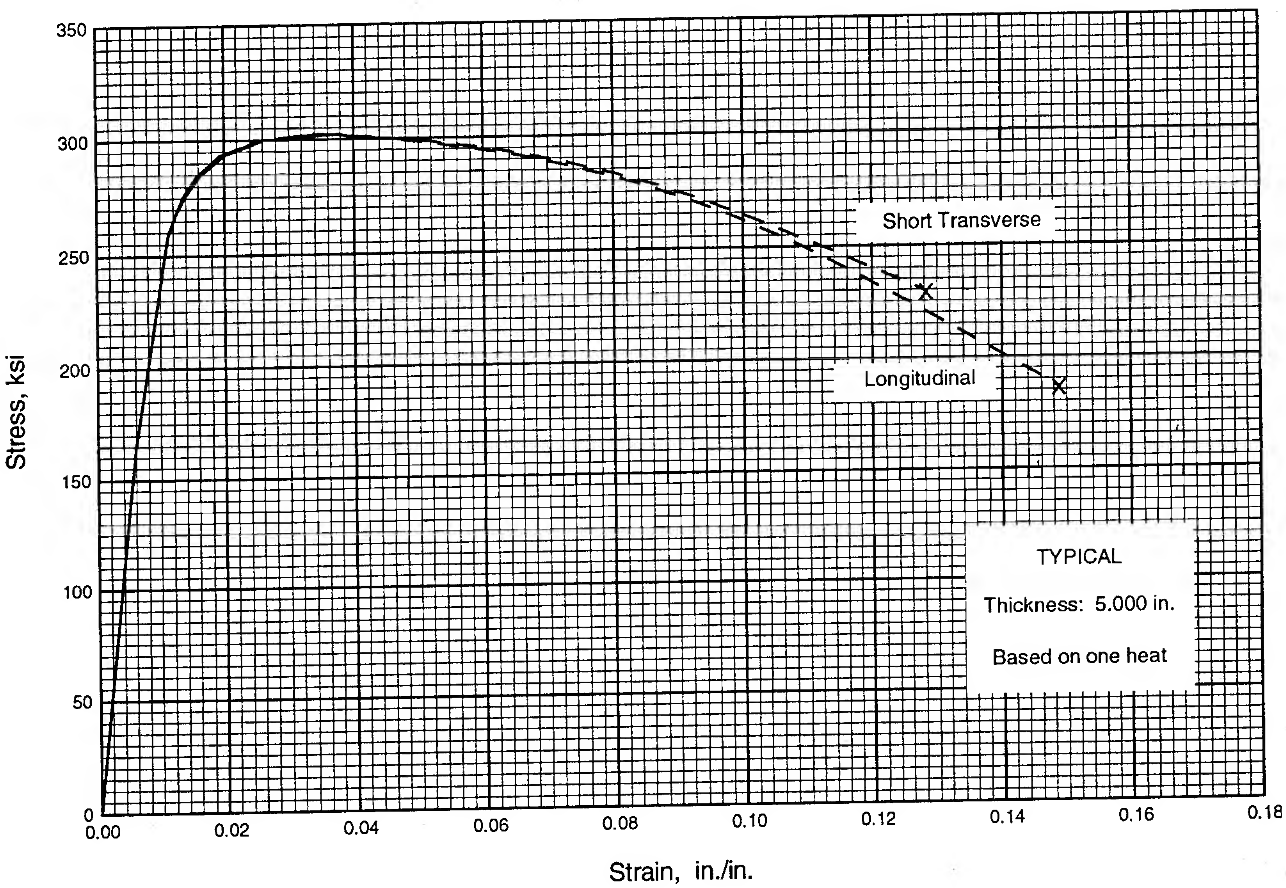

FIGURE 2.5.3.2.6(c). *Typical tensile stress-strain curve (full-range) at room temperature for AerMet 100 steel bar, heat treated to 290-310 ksi.*

2.6 Precipitation and Transformation-Hardening Steels (Stainless)

2.6.0 COMMENTS ON PRECIPITATION AND TRANSFORMATION-HARDENING STEELS (STAINLESS)

2.6.0.1 *Metallurgical Considerations.*—The transformation and precipitation-hardening stainless steels are martensitic or semiaustenitic stainless steels that are hardenable by heat treatment.* The martensitic alloys require only a single step heat treatment to develop maximum strength. The others are austenitic in the fully annealed condition but become martensitic during subsequent heat treatment or as a result of extensive cold working. During a final heat treatment designed to temper the martensite, several of these steels are hardened further by the precipitation of copper, aluminum, or titanium.

Some dimensional change may be experienced during the heat treatment of the semiaustenitic steels. A dimensional expansion of approximately 0.0045-in./in. occurs during the transformation from the austenitic to the martensitic condition; during aging, a contraction of about 0.0005-in./in. takes place.

2.6.0.2. *Manufacturing Considerations.*—The martensitic precipitation-hardening steels, before age hardening, are similar to the straight-chromium martensitic stainless steels (Type 410 or 431) in their general fabricating characteristics. The semiaustenitic grades, in the annealed condition, are similar to the austenitic stainless steels (Types 301, etc.) in this respect, and are readily cold formed. Forming of hardened steels after final heat treatment should be avoided.

These alloys can be welded by the conventional methods used for the austenitic stainless steels. Inert-gas-shielded welding is recommended to prevent the loss of titanium or aluminum in certain of these alloys. Postweld annealing is recommended for some grades.

The heat treatments for these steels are compatible with the cycles used for honeycomb panel brazing. Vapor blasting of scaled parts, after final heat treatment, is recommended because of the hazards of intergranular corrosion in inadequately controlled acids pickling operations.

2.6.0.3 *Environmental Considerations.*—The precipitation-hardening stainless steels have good strength and oxidation and corrosion resistance in their service range. Prolonged exposures above 600 F and below the tempering range may cause further hardening, with possible decrease in ductility. Prolonged exposures in or above the temperature range result in loss of strength due to overtempering, overaging, or reaustenizing.

2.6.1 AM-350

2.6.1.0 *Comments and Properties.*—AM-350 has high strength up to 800 F and good oxidation resistance up to about 1000 F. The alloy can be hardened by subzero cooling and tempering (Condition SCT).

Manufacturing Considerations.—AM-350 is readily formed, welded, and brazed. Its forming characteristics are similar to the AISI 300 series stainless steels; however, it does have a higher rate of strain hardening. When fabricating AM-350 in the annealed condition, proper design allowance must be made for growth which occurs upon hardening. To obtain proper response to the SCT treatment after welding, the alloy must be reannealed.

Environmental Considerations.—AM-350 shows good corrosion-resisting properties in ordinary atmospheres and also in a number of chemical environments. Exposure in the 600 to 800 F range for 1,000 hours at stress levels below the short-time yield strength tends to increase room-temperature yield strength and room-temperature tensile strength slightly. Exposure to 800 F results in a decrease in elongation. Typical data are presented in Table 2.6.1.0(a).

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* Heat treating procedures for these steels are specified in MIL-H-6875 and are further described in producers' literature.

TABLE 2.6.1.0(a). *Effect of Elevated Temperature Exposure on Typical Tensile Properties of AM-350 Alloy in the SCT 850 Condition*

Exposure temp., F	Exposure stress, ksi	Exposure time, hr	Room-temperature properties		
			TUS, ksi	TYS, ksi	e, %
RT	...	...	201	158	12.0
600	60	1,000	198	162	14.0
700	60	1,000	204	169	11.0
800	60	1,000	220	190	7.0
600	90	1,000	202	177	13.0
700	90	1,000	206	180	11.0
800	90	1,000	214	192	7.0

Specifications and Properties.—A material specification for AM-350 stainless steel is presented in Table 2.6.1.0(b). The room-temperature properties of AM-350 in the SCT 850 condition are shown in Table 2.6.1.0(c). Figure 2.6.1.0 presents elevated temperature physical property information.

TABLE 2.6.1.0(b). *Material Specifications for AM-350 Stainless Steel*

Specification	Form
AMS 5548	Sheet and strip

2.6.1.1 *SCT 850 Condition.*—Effect of temperature on various mechanical properties of AM-350 is presented in Figures 2.6.1.1.1 through 2.6.1.1.4. Typical stress-strain and tangent-modulus curves at several temperatures are shown in Figures 2.6.1.1.6(a) and (b).

TABLE 2.6.1.0(c). *Design Mechanical and Physical Properties of AM-350 Stainless Steel Sheet and Strip*

Specification	AMS 5548
Form	Sheet and strip[a]
Condition	SCT 850
Thickness, in.	≤ 0.187
Basis	S
Mechanical Properties:	
F_{tu}, ksi:	
L	183
LT	185
F_{ty}, ksi:	
L	147
LT	150
F_{cy}, ksi:	
L	163
LT	...
F_{su}, ksi	121
F_{bru}, ksi:	
(e/D = 1.5)	...
(e/D = 2.0)	373
F_{bry}, ksi:	
(e/D = 1.5)	...
(e/D = 2.0)	252
e, percent:	
LT	10[b]
E, 10^3 ksi	29.0
E_c, 10^3 ksi	30.0
G, 10^3 ksi	11.0
μ	0.32
Physical Properties:	
ω, lb/in.^{3}	0.282
C, Btu/(lb)(F)	0.12 (32 to 212 F)
K and α	See Figure 2.6.1.0

[a]Test direction longitudinal for widths less than 9 in.; transverse for widths 9 in. and over.

[b]Elongation is 8 percent for sheet thickness in the range 0.010 to 0.050 inch. Listed value is for thickness > 0.050 inch.

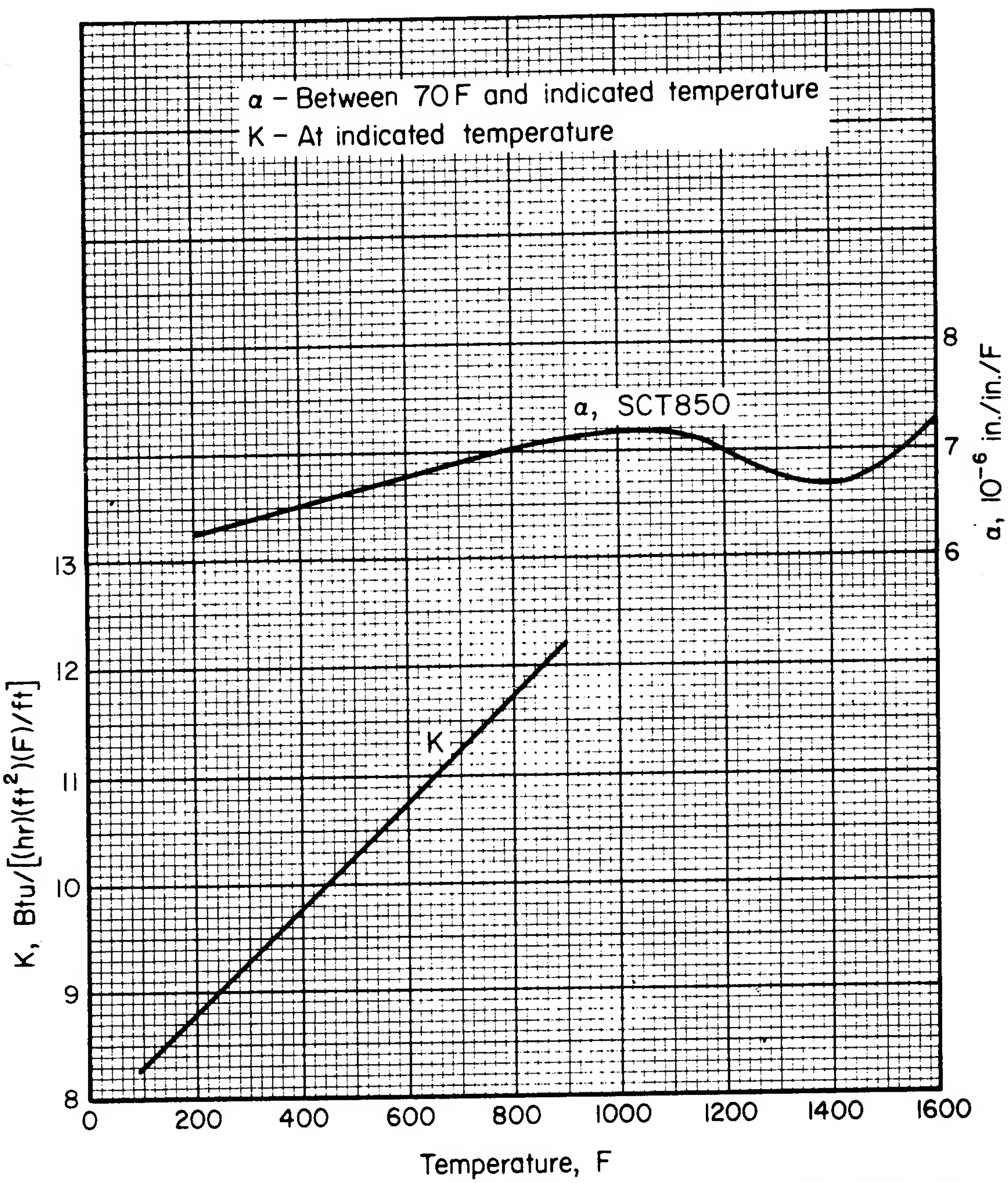

FIGURE 2.6.1.0. *Effect of temperature on the physical properties of AM-350 stainless steel.*

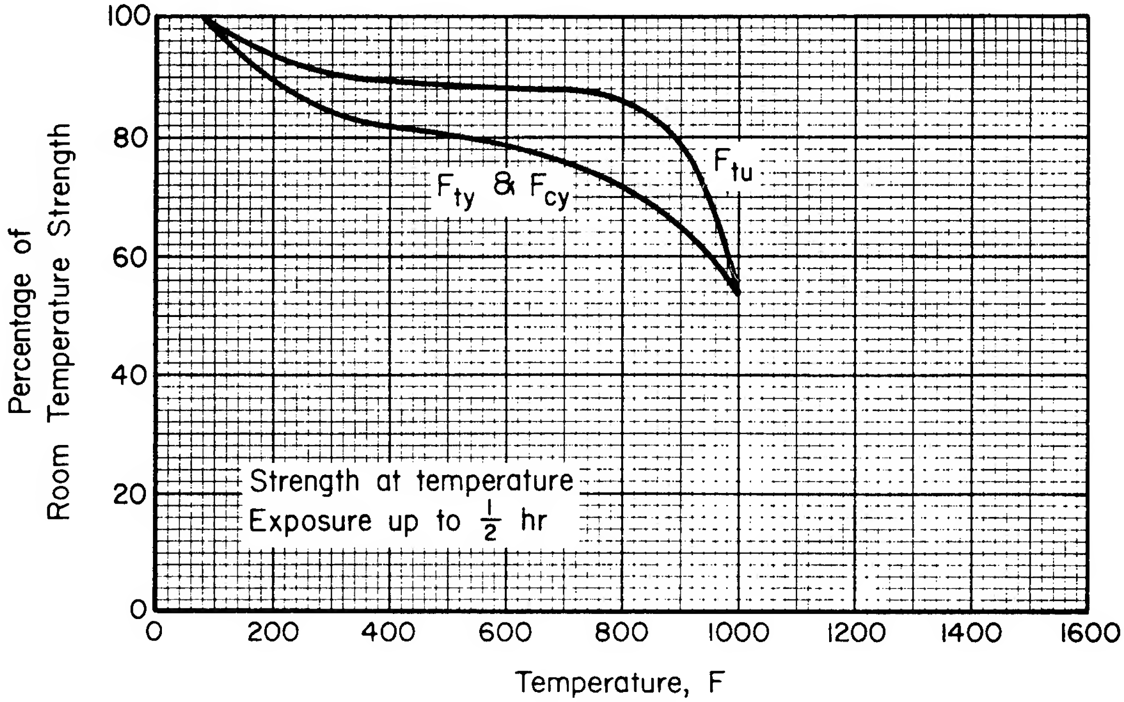

FIGURE 2.6.1.1.1. *Effect of temperature on the tensile ultimate strength (F_{tu}), the tensile yield strength (F_{ty}), and the compressive yield strength (F_{cy}) of AM-350 (SCT 850) stainless steel sheet.*

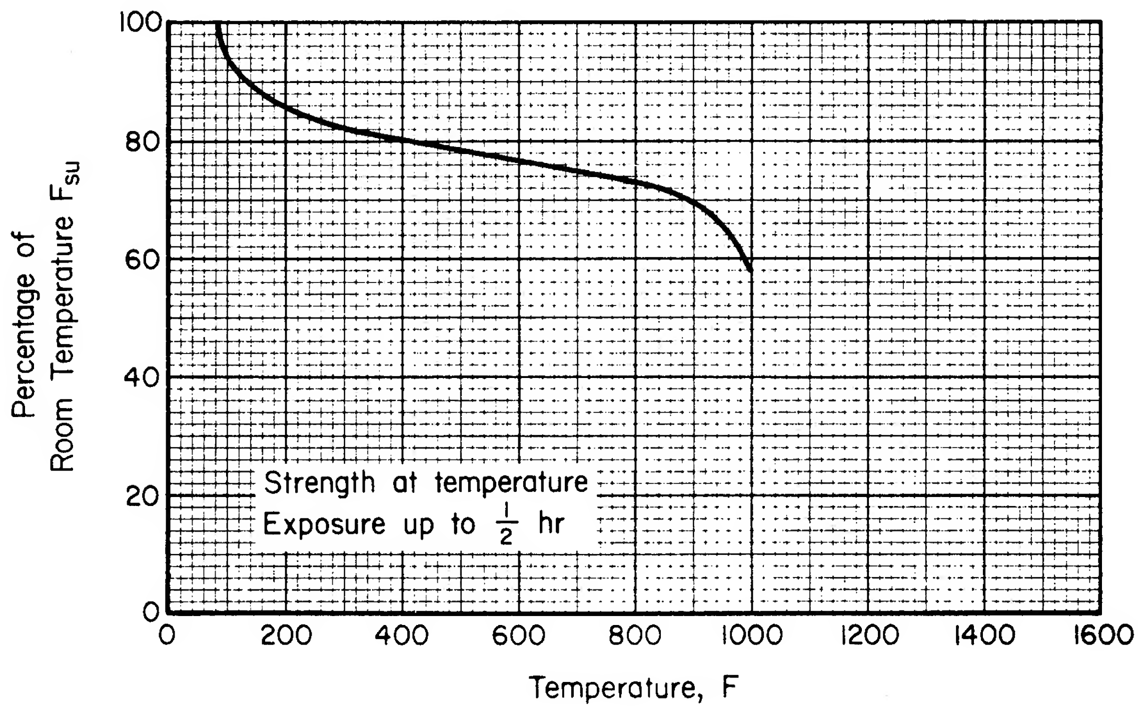

FIGURE 2.6.1.1.2. *Effect of temperature on the shear ultimate strength (F_{su}) of AM-350 (SCT 850) stainless steel sheet.*

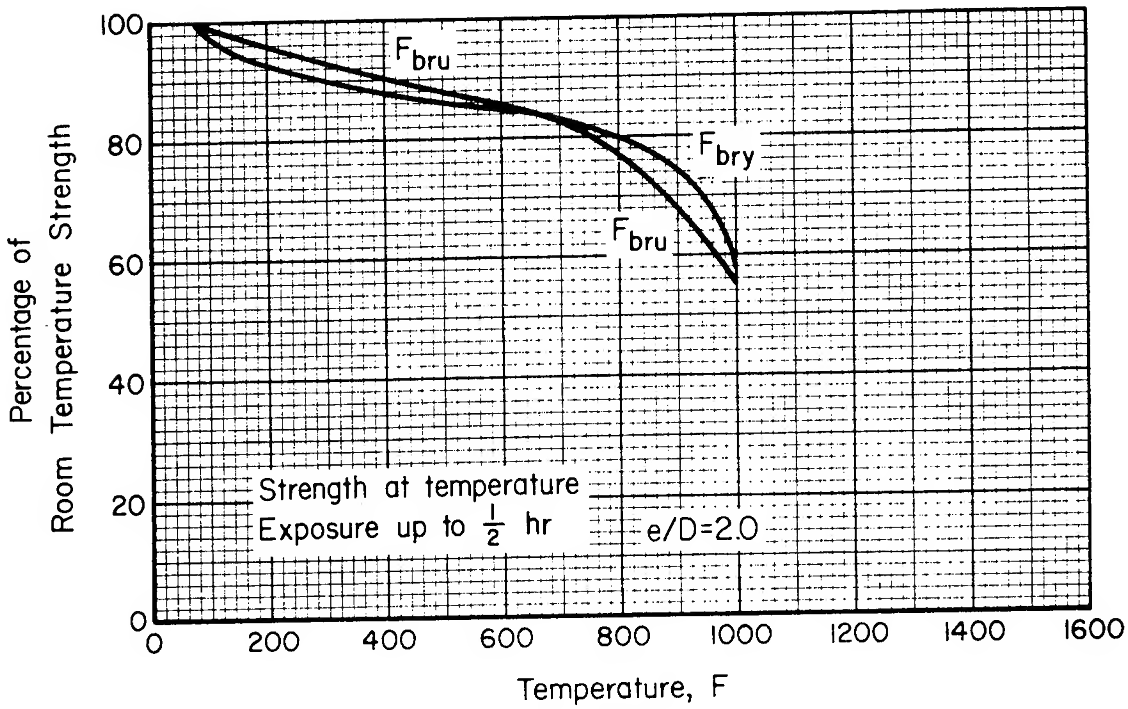

FIGURE 2.6.1.1.3. *Effect of temperature on the bearing ultimate strength (F_{bru}) and the bearing yield strength (F_{bry}) of AM-350 (SCT 850) stainless steel sheet.*

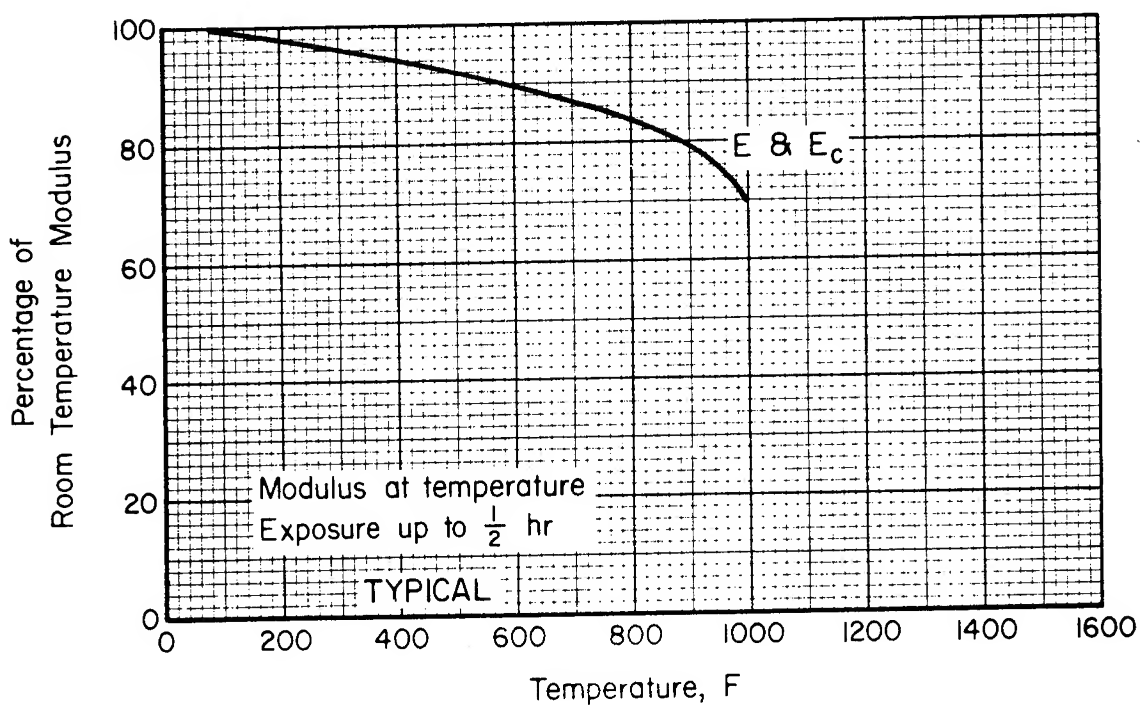

FIGURE 2.6.1.1.4. *Effect of temperature on the tensile and compressive moduli (E and E_c) of AM-350 (SCT 850) stainless steel sheet.*

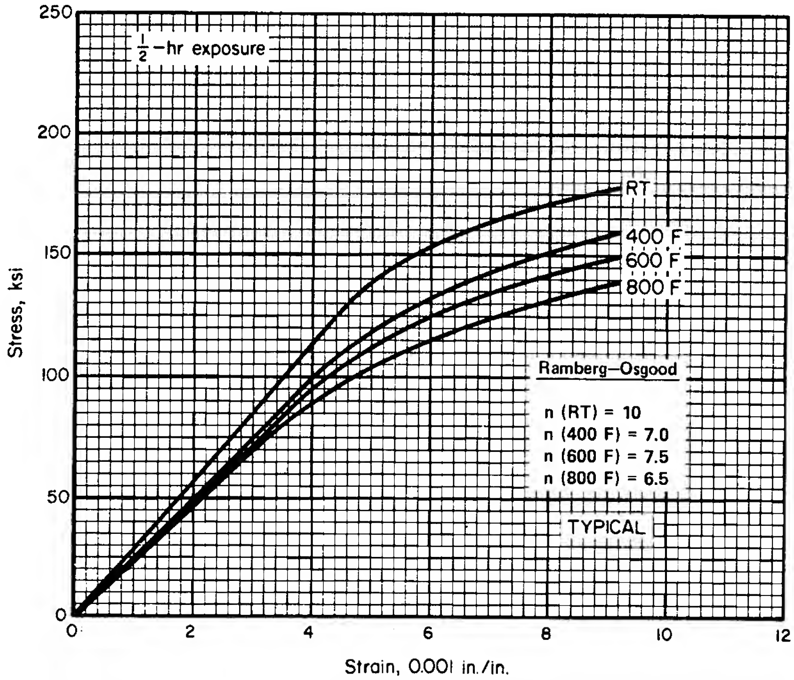

FIGURE 2.6.1.1.6(a). *Typical tensile stress-strain curves at various temperatures for AM-350 (SCT850) stainless steel sheet.*

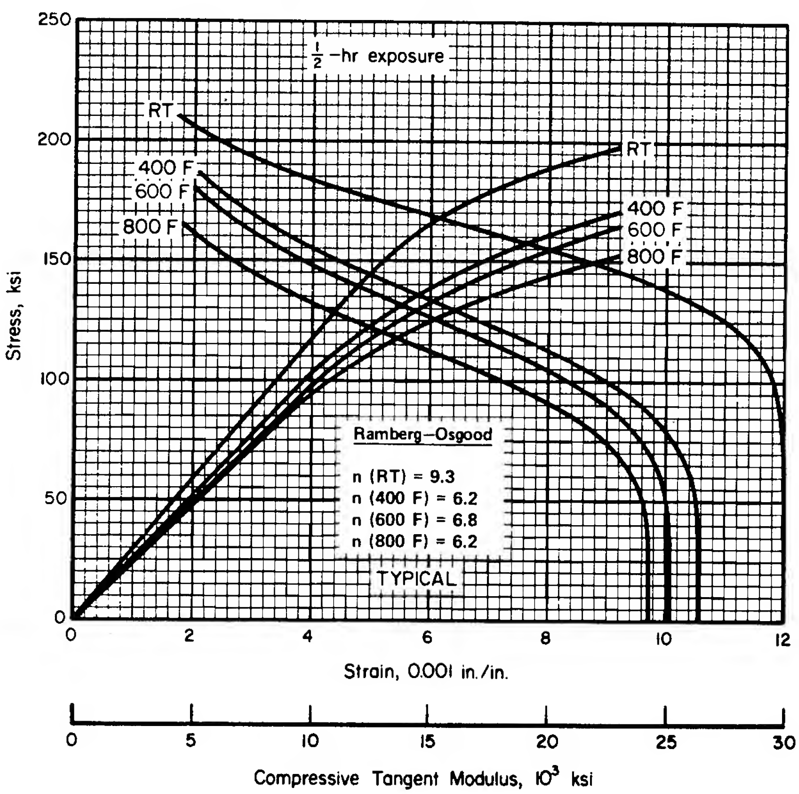

FIGURE 2.6.1.1.6(b). *Typical compressive stress-strain and compressive tangent-modulus cuves at various temperatures for AM-350 (SCT850) stainless steel sheet.*

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2.6.2 AM-355

2.6.2.0 *Comments and Properties.*—AM-355, like AM-350, has high strength up to 800 F and good oxidation resistance up to 1000 F. The AM-355 alloy is generally hardened by subzero cooling and tempering (Condition SCT).

AM-355 is available in all mill products. The manufacturing considerations for AM-355 are similar to those for AM-350. Machining of AM-355 bars and forgings is best accomplished after overtempering at 1000 to 1100 F.

The differences between AM-350 and AM-355 are a result of higher carbon, lower chromium, and reduced delta ferrite in AM-355. This difference in composition makes AM-355 slightly stronger but slightly less corrosion resistant than AM-350.

Environmental Considerations.—Exposure in the 600 to 800 F range for 100 hours at stress levels below the short time yield strength tends to increase room-temperature yield strength and room-temperature tensile strength slightly, with little change in elongation. Typical data are shown in Table 2.6.2.0(a).

Specifications and Properties.—Material specifications for AM-355 are presented in Table 2.6.2.0(b). The room temperature properties of AM-355 SCT are shown in Table 2.6.2.0(c) through (e). The physical properties of this alloy are presented in Figure 2.6.2.0.

TABLE 2.6.2.0(b). *Material Specifications for AM-355 Stainless Steel*

Specification	Form
AMS 5547	Sheet and strip
AMS 5549	Plate
AMS 5743	Bar, forging, and forging stock

2.6.2.1 *SCT Condition.*—Elevated-temperature properties for AM-355 in the SCT (subzero cooled and tempered) condition are presented in Figures 2.6.2.1.1 through 2.6.2.1.4.

TABLE 2.6.2.0(a). *Effect of Elevated Temperature Exposure on Typical Tensile Properties of AM-355 Alloy in the SCT 850 Condition*

Exposure temp., F	Exposure stress, ksi	Exposure time, hr	Room-temperature properties		
			TUS, ksi	TYS, ksi	e, %
RT	...	...	211	170	11.5
600	66	1,000	213	172	12.0
700	65	1,000	218	178	10.5
800	62	1,000	227	200	12.5
600	99	1,000	214	180	10.5
700	97	1,000	218	189	11.5
800	93	1,000	224	204	12.5

TABLE 2.6.2.0(c). *Design Mechanical and Physical Properties of AM-355 Stainless Steel*

Specification	AMS 5547		AMS 5743	
Form	Sheet and strip[a]		Bar and forging	
Condition	SCT850[b]	SCT1000	SCT850[b]	SCT1000
Thickness or diameter, in.	0.005-0.187	0.010-0.187	...	...
Basis	S	S	S	S
Mechanical Properties:				
F_{tu}, ksi:				
L	188	...	200	170
LT	190	165	...	...
F_{ty}, ksi:				
L	162	...	165	155
LT	165	140	...	...
F_{cy}, ksi:				
L	180	...	...	...
LT	...	...	...	...
F_{su}, ksi	124	...	...	...
F_{bru}, ksi:				
(e/D = 1.5)	...	...	...	...
(e/D = 2.0)	383	...	...	...
F_{bry}, ksi:				
(e/D = 1.5)	...	...	...	...
(e/D = 2.0)	278	...	...	...
e, percent:				
L	...	...	10	12
LT	[c]	10	...	...
RA, percent:				
L	...	...	20	25
E, 10^3 ksi	29.0			
E_c, 10^3 ksi	29.0			
G, 10^3 ksi	11.0			
μ	0.32			
Physical Properties:				
ω, lb/in.^{3}	0.282			
C, K, and α	See Figure 2.6.2.0			

[a]Test direction longitudinal for widths less than 9 inches; transverse for widths 9 inches and over.
[b]Note: Condition SCT850 has been superseded by Condition SCT1000 in the applicable specifications. The tensile properties in these columns are the values previously specified for Condition SCT850.
[c]See Table 2.6.2.0(e).

TABLE 2.6.2.0(d). *Design Mechanical and Physical Properties of AM-355 Stainless Steel Plate*

Specification	AMS 5549			
Form	Plate[a]			
Condition	SCT850[b]			SCT 1000
Thickness, in.	<0.375	0.375-1.000	>1.000	<0.187
Basis	S	S	S	S
Mechanical Properties:				
F_{tu}, ksi:				
L	188	...	...	...
LT	190	190	190	165
F_{ty}, ksi:				
L	162	...	...	...
LT	165	150	c	140
F_{cy}, ksi:				
L	180	...	...	...
LT	...	...	...	...
F_{su}, ksi	124	...	...	...
F_{bru}, ksi:				
(e/D = 1.5)	...	...	...	...
(e/D = 2.0)	383	...	...	...
F_{bry}, ksi:				
(e/D = 1.5)	...	...	...	...
(e/D = 2.0)	278	...	...	...
e, percent:				
LT	10	10	10	12
E, 10^3 ksi	29.0			
E_c, 10^3 ksi	29.0			
G, 10^3 ksi	11.0			
μ	0.32			
Physical Properties:				
ω, lb/in.^{3}	0.282			
C, K, and α	See Figure 2.6.2.0			

[a]Test direction longitudinal for widths less than 9 inches; transverse for widths 9 inches and over.
[b]Note: Condition SCT850 has been superseded by Condition SCT1000 in the applicable specifications. The tensile properties in these columns are the values previously specified for Condition SCT850.
[c]As agreed upon by purchaser and vendor.

TABLE 2.6.2.0(e). *Minimum Elongation Values for AM-355 (SCT 850) Stainless Steel Sheet and Strip*

Thickness, inches	e (LT), percent in 2 inches
0.005 to 0.0015	2
Over 0.0015 to 0.0020	3
Over 0.0020 to 0.0050	5
Over 0.0050 to 0.0100	7
Over 0.0100 to 0.1875	8

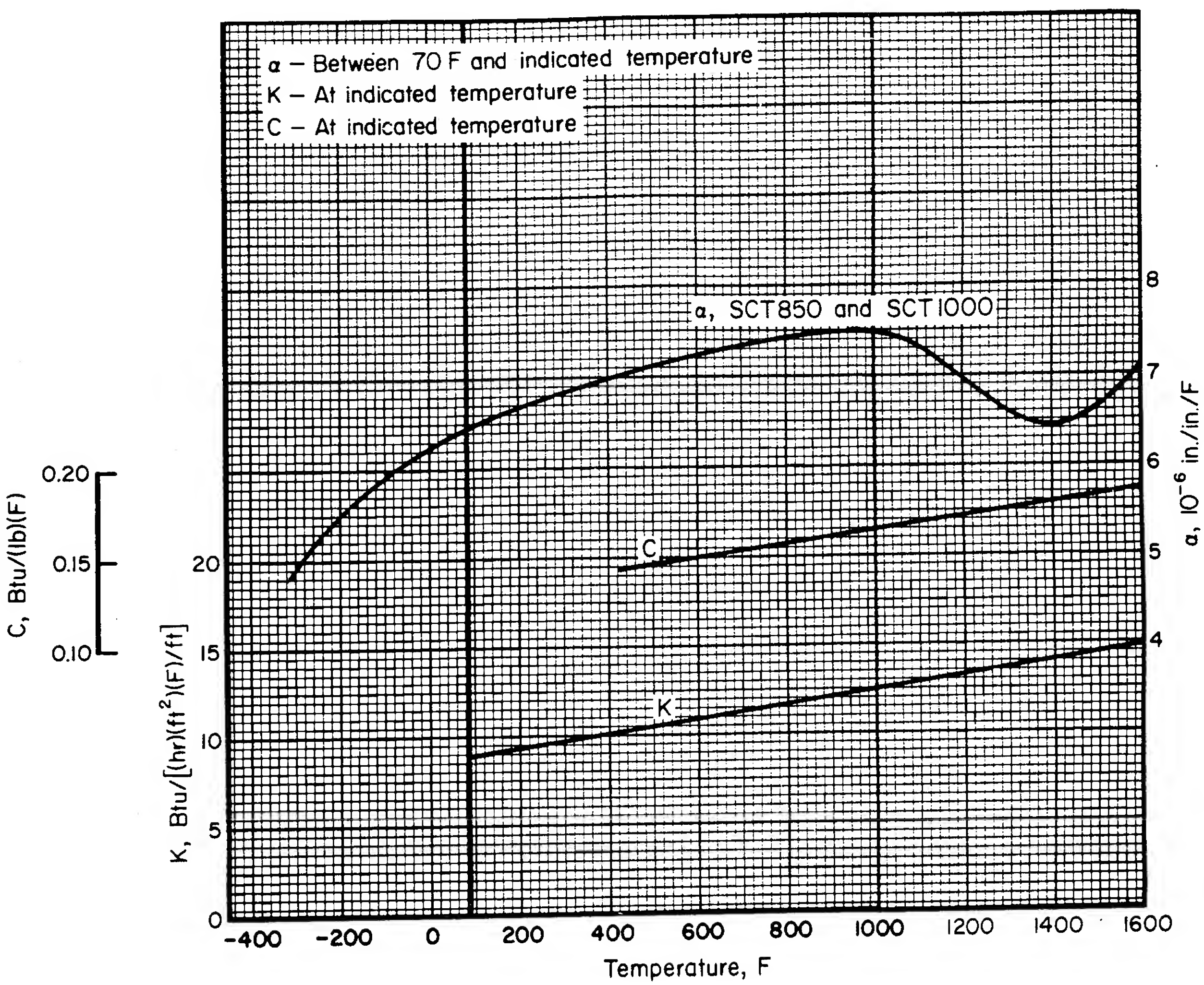

FIGURE 2.6.2.0. *Effect of temperature on the physical properties of AM-355 stainless steel.*

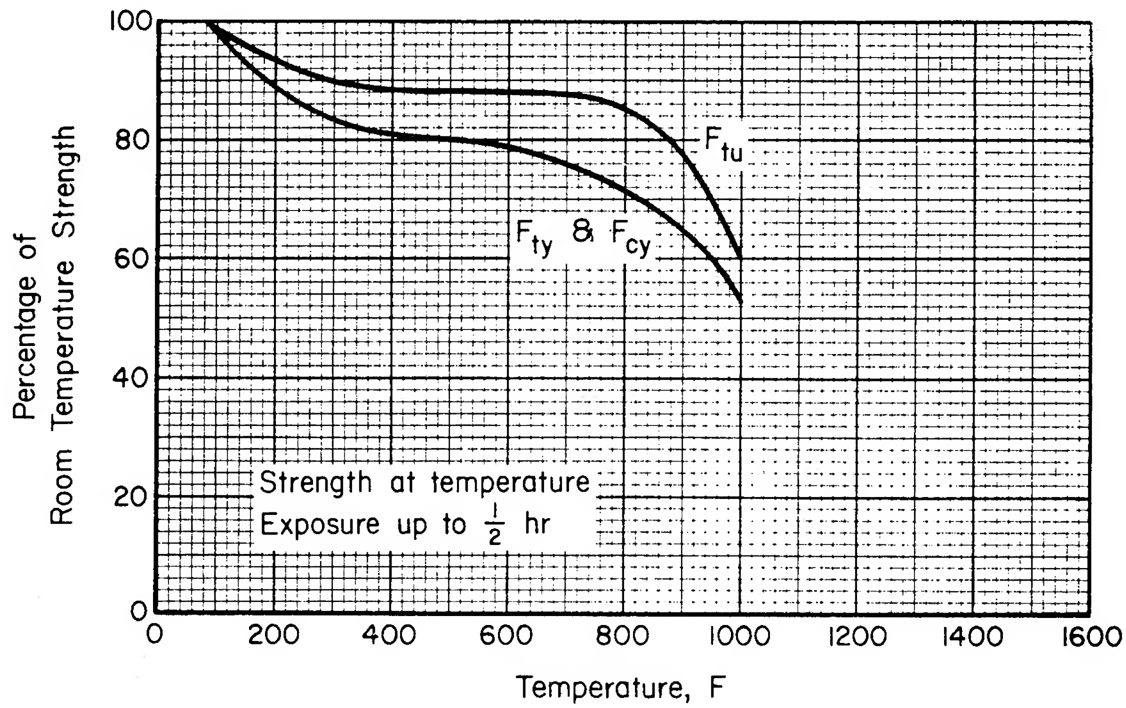

FIGURE 2.6.2.1.1. *Effect of temperature on the tensile ultimate strength (F_{tu}), the tensile yield strength (F_{ty}), and the compressive yield strength (F_{cy}) of AM-355 (SCT 850) stainless steel (all products).*

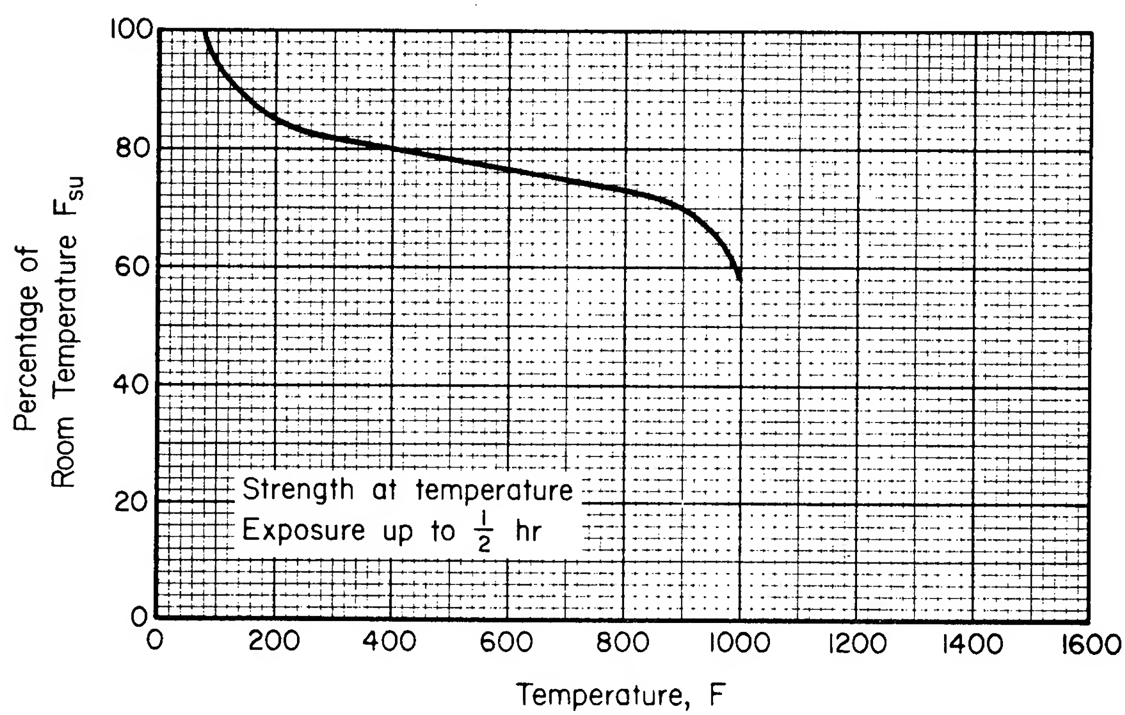

FIGURE 2.6.2.1.2. *Effect of temperature on the shear ultimate strength (F_{su}) of AM-355 (SCT 850) stainless steel (all products).*

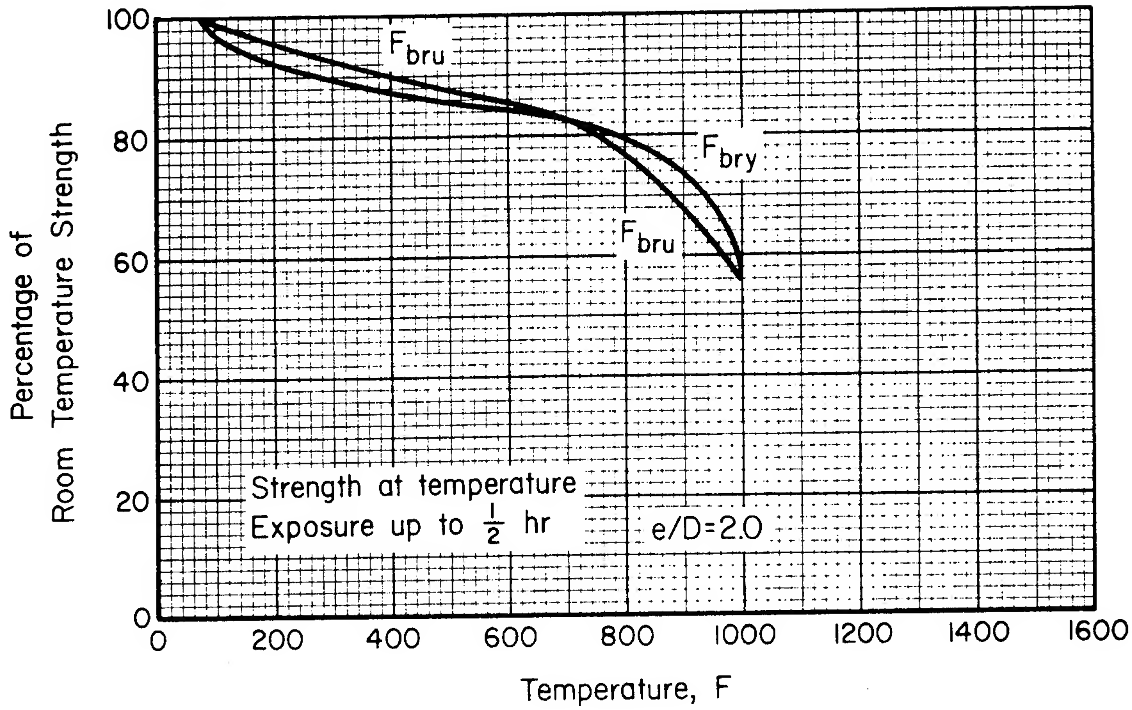

FIGURE 2.6.2.1.3. *Effect of temperature on the bearing ultimate strength (F_{bru}) and the bearing yield strength (F_{bry}) of AM-355 (SCT 850) stainless steel sheet.*

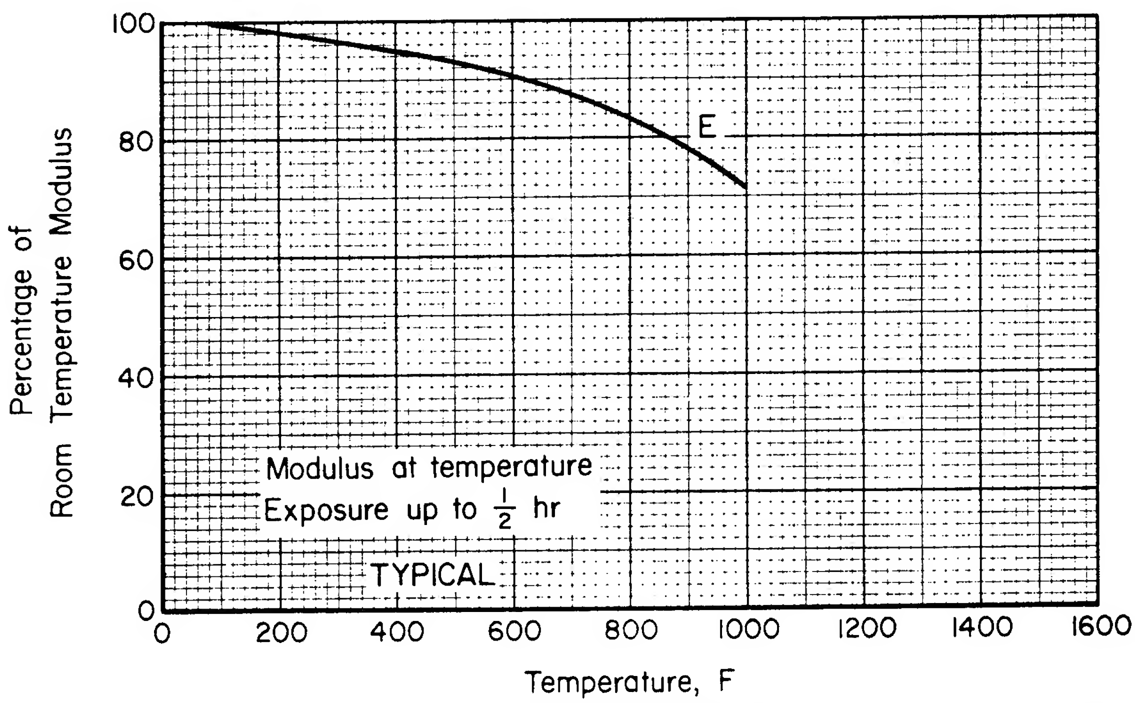

FIGURE 2.6.2.1.4. *Effect of temperature on the tensile modulus (E) of AM-355 (SCT 850) stainless steel (all products).*

2.6.3 CUSTOM 450

2.6.3.0 *Comments and Properties.*—Custom 450 is a martensitic, precipitation-hardening stainless steel used for parts requiring corrosion resistance and high strength at temperatures up to 800 F for aged conditions. It is available in the form of forgings, billet, bar, wire, strip, and welded tubing.

Manufacturing Considerations.—Custom 450 is normally supplied and fabricated in the solution-treated condition except wire for cold heading is supplied in the H1150M condition. Forming, machining, and joining operations are similar to those employed for other precipitation hardening stainless steels.

Heat Treatment.—Among the alloys of its type, Custom 450 is the only one recommended for use in the solution-treated condition at temperatures up to 500 F. The alloy can also be heat treated to various strength levels having a wide range of properties. Consult the applicable material specification or MIL-H-6875 for specific heat treatment procedures.

In all heat treat conditions, Custom 450 has excellent ductility and toughness. Cryogenic properties are optimum in the H1150 condition. Maximum strength is achieved with the 900 F aging treatment while optimum fatigue life is exhibited with a 1050 F age.

When the as-supplied solution-treated condition is altered during processing by hot working, severe cold working, or welding, parts should be resolution annealed prior to aging. A dimensional contraction of about 0.0002 in./in. with the 900 F age and about 0.001 in./in. for the 1050 F aging treatment can be expected.

Environmental Considerations.—The general corrosion resistance of Custom 450 is similar to AISI Type 304 stainless steel. Custom 450 shows excellent resistance to atmosphere corrosion and mild chemical environments. It has good resistance to stress corrosion cracking in the solution-treated condition. Like all martensitic precipitation hardening alloys, if stress corrosion is of concern, it should be aged at the highest temperature compatible with strength requirements. It offers the best resistance to stress corrosion cracking and hydrogen embrittlement when aged at 1150 F. The general corrosion resistance is very slightly decreased by the higher aging temperatures.

Material specifications for Custom 450 are shown in Table 2.6.3.0(a). The room-temperature mechanical properties are presented in Tables 2.6.3.0(b) and (c). The effect of temperature on thermal expansion is shown in Figure 2.6.3.0.

TABLE 2.6.3.0(a). *Material Specifications for Custom 450 Stainless Steel*

Specification	Form
AMS 5763	Bar, forging, tubing, wire, and ring (air melted)
AMS 5773	Bar, forging, tubing, wire, and ring (CEM)

2.6.3.1 *H900 Condition.*—Elevated temperature curves are presented in Figures 2.6.3.1.1, 2.6.3.1.2, and 2.6.3.1.5. A tensile stress-strain curve at room temperature is shown in Figure 2.6.3.1.6. Fatigue data at room temperature are presented in Figure 2.6.3.1.8.

2.6-3.2 *H1050 Condition.*—Elevated temperature curves are presented in Figures 2.6.3.2.1, 2.6.3.2.2, and 2.6.3.2.5. A tensile stress-strain curve at room temperature is shown in Figure 2.6.3.2.6. Fatigue data at room temperature are presented in Figure 2.6.3.2.8.

TABLE 2.6.3.0(b). *Design Mechanical and Physical Properties of Custom 450 Stainless Steel Bar*

Specification	AMS 5763		
Form	Bar		
Condition	Solution Treated	H900	H1050
Thickness or diameter, in.	≤8.000	≤8.000	≤8.000
Basis	S	S	S[a]
Mechanical Properties:			
F_{tu}, ksi:			
L	125	180	145
ST	...	179	144
F_{ty}, ksi:			
L	95	170	135
ST	...	168	133
F_{cy}, ksi:			
L	...	175	143
ST	...	173	141
F_{su}, ksi	...	114	93
F_{bru}, ksi:			
(e/D = 1.5)	...	298	239
(e/D = 2.0)	...	381	307
F_{bry}, ksi:			
(e/D = 1.5)	...	265	204
(e/D = 2.0)	...	326	257
e, percent:			
L	10	10	12
RA, percent:			
L	40	40	45
E, 10^3 ksi	28.0	29.0	
E_c, 10^3 ksi	...	31.0	
G, 10^3 ksi	...	11.2	
μ	...	0.29	
Physical Properties:			
ω, lb/in.^{3}	0.28		
C, Btu/(lb)(F)	...		
K, Btu/[(hr)(ft^2)(F)/ft]	...		
α, 10^{-6} in./in./F	See Figure 2.6.3.0		

[a]Suppliers guaranteed minimum properties.

TABLE 2.6.3.0(c). *Design Mechanical and Physical Properties of Custom 450 Stainless Steel Bar*

Specification	AMS 5773						
Form	Bar						
Condition	Solution treated	H900	H950	H1000	H1050	H1100	H1150
Thickness or diameter, in.	≤12.000						
Basis	S	S	S	S	S	S	S
Mechanical Properties:							
F_{tu}, ksi:							
L	125	180	170	160	145	130	125
T	...	180	170	160	145	130	125
F_{ty}, ksi:							
L	95	170	160	150	135	105	75
T	...	170	160	150	135	105	75
F_{cy}, ksi:							
L	...	175	...	...	143	...	...
T	...	173	...	...	141	...	...
F_{su}, ksi	...	114	...	...	93	...	...
F_{bru}, ksi:							
(e/D = 1.5)	...	298	...	...	239	...	...
(e/D = 2.0)	...	381	...	...	307	...	...
F_{bry}, ksi:							
(e/D = 1.5)	...	265	...	...	204	...	...
(e/D = 2.0)	...	326	...	...	257	...	...
e, percent:							
L	10	10	10	12	12	16	18
T	...	6	7	8	9	11	12
R, percent:							
L	40	40	40	45	45	50	55
T	...	20	22	27	30	30	35
E, 10^3 ksi	28.0	29.0					
E_c, 10^3 ksi	...	31.0					
G, 10^3 ksi	...	11.2					
μ	...	0.29					
Physical Properties:							
ω, lb/in.^{3}	0.28						
C, Btu/(lb)(F)	...						
K, Btu/[(hr)(ft^2)(F)/ft]	...						
α, 10^{-6} in./in./F	See Figure 2.6.3.0						

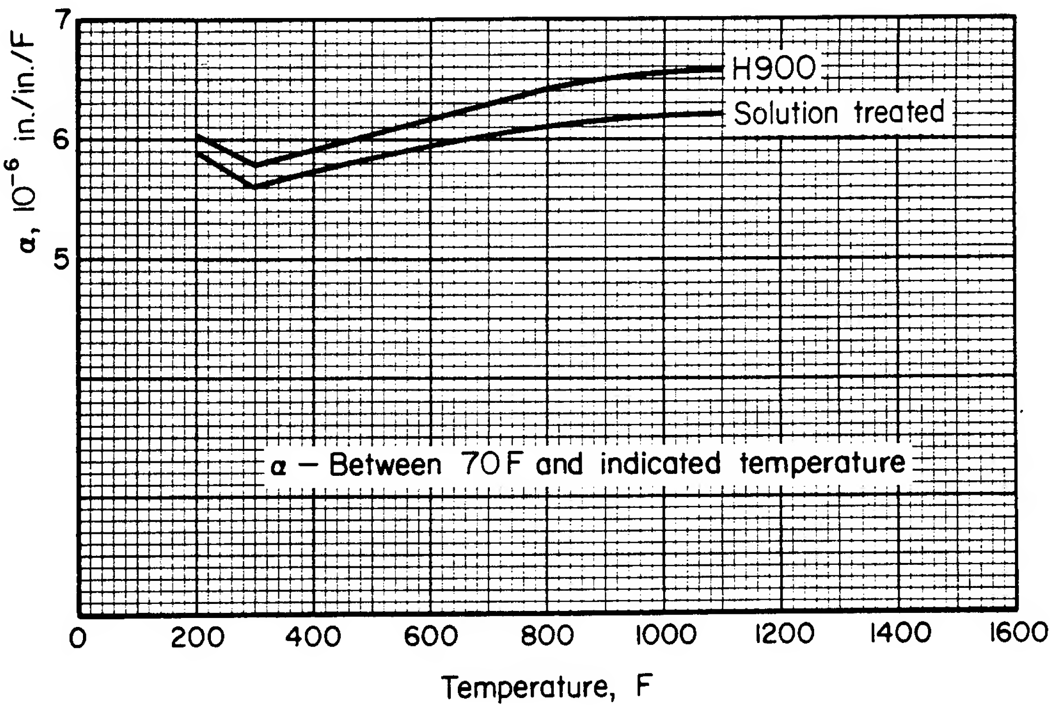

FIGURE 2.6.3.0 *Effect of temperature on the physical properties of Custom 450 stainless steel.*

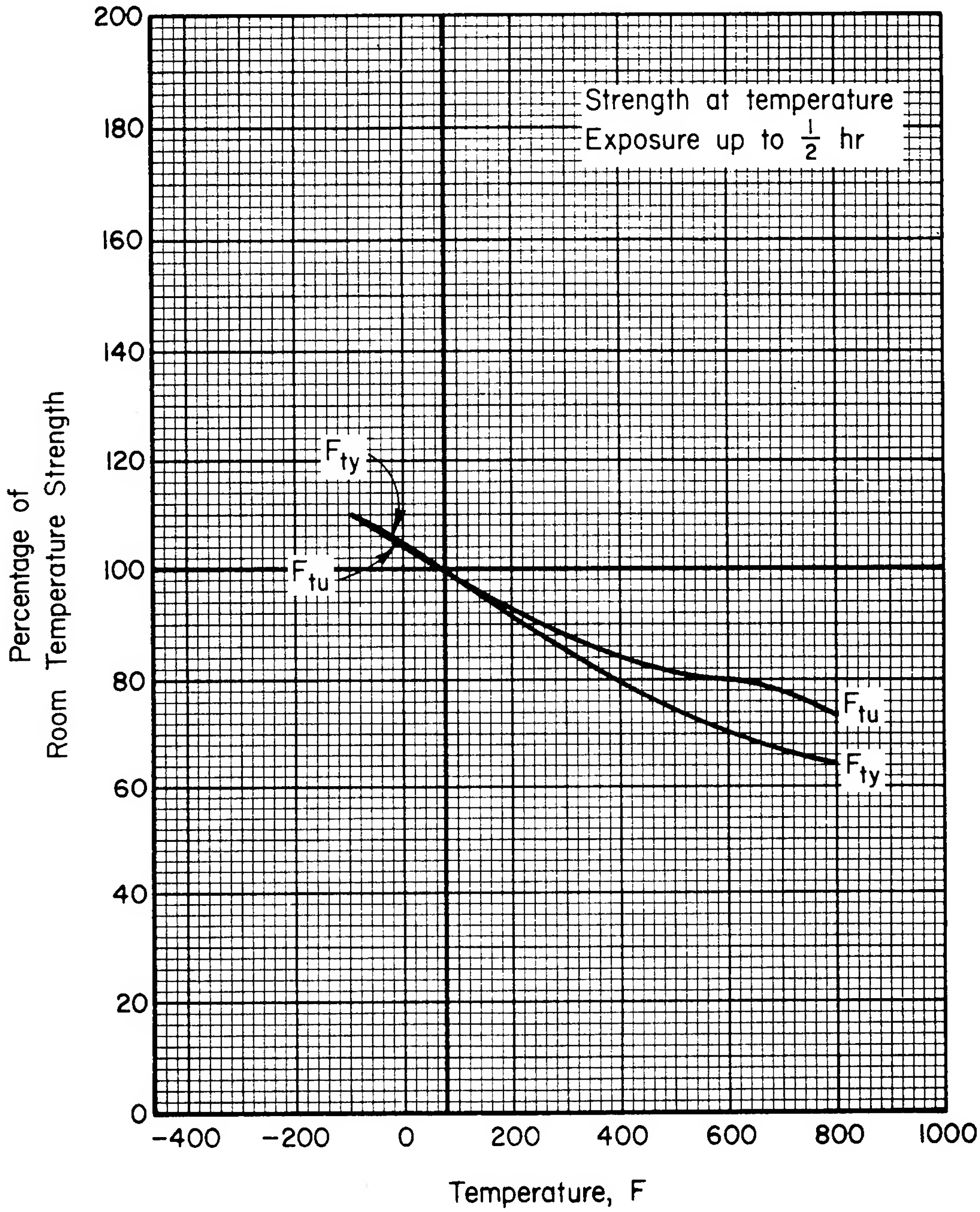

FIGURE 2.6.3.1.1. *Effect of temperature on the tensile ultimate strength (F_{tu}) and the tensile yield strength (F_{ty}) of Custom 450 (H900) stainless steel bar.*

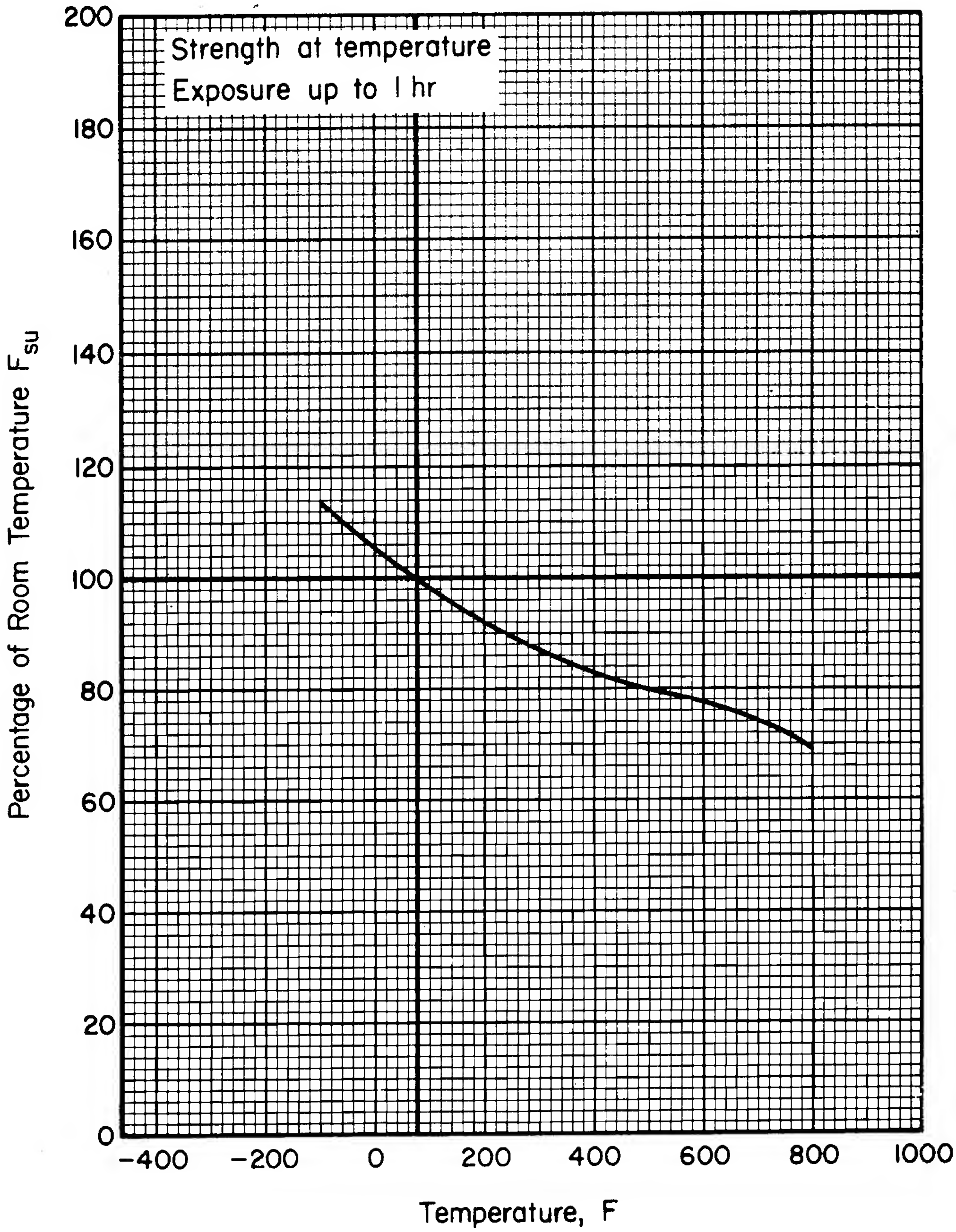

FIGURE 2.6.3.1.2. *Effect of temperature on the ultimate shear strength (F_{su}) of Custom 450 (H900) stainless steel bar.*

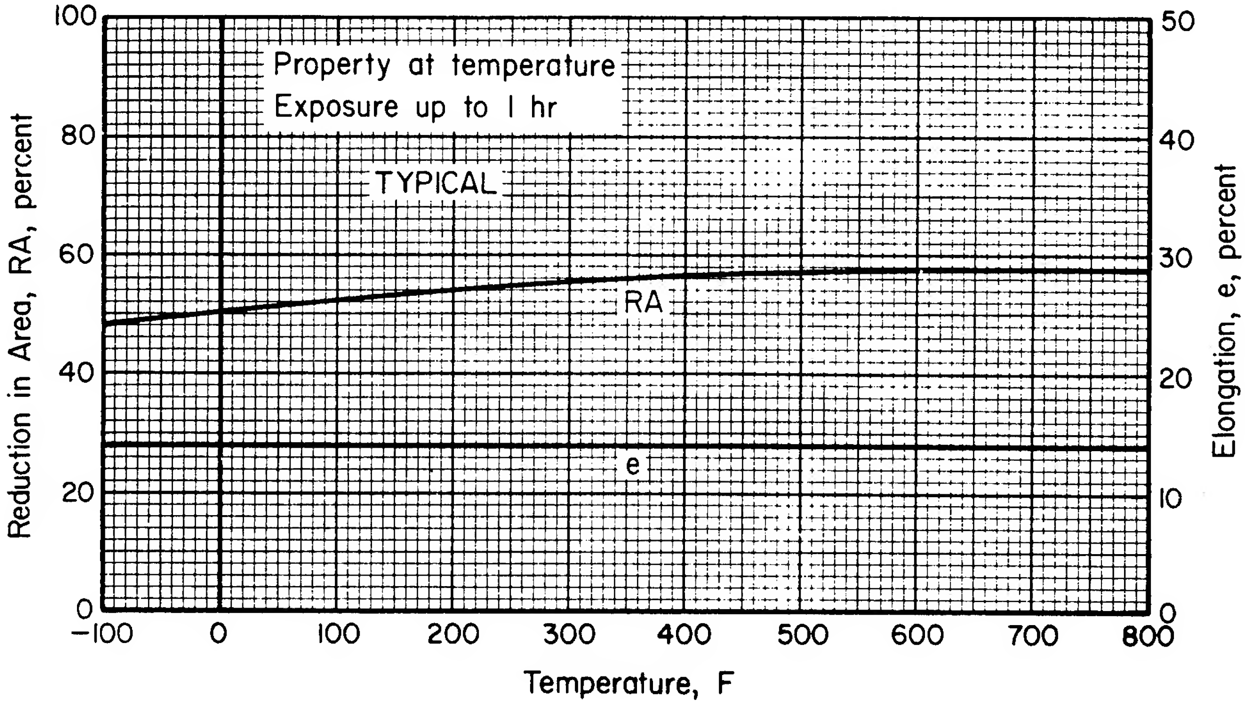

FIGURE 2.6.3.1.5. *Effect of temperature on the elongation (e) and the reduction of area (RA) of Custom 450 (H900) stainless steel bar.*

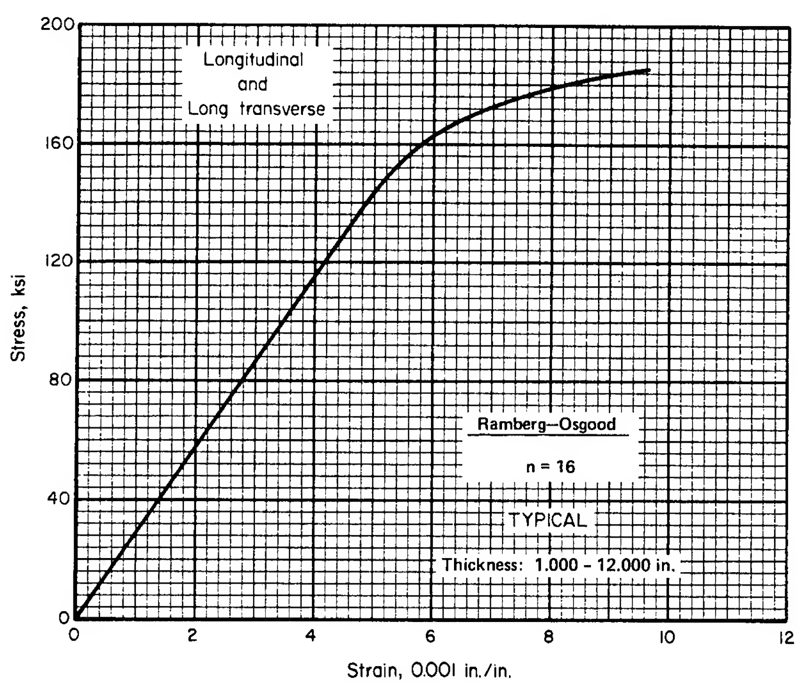

FIGURE 2.6.3.1.6. *Typical tensile stress-strain curve for Custom 450 (H900) stainless steel bar at room temperature.*

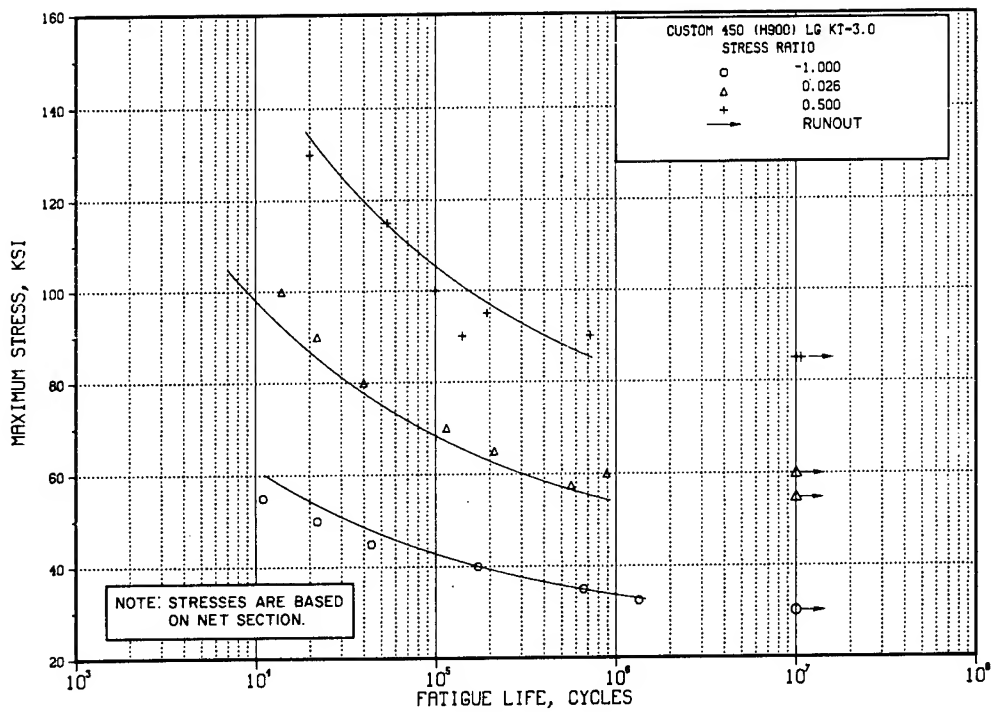

FIGURE 2.6.3.1.8. *Best-fit S/N curves for notched, K_t = 3.0, Custom 450 (H900) stainless steel (ESR) bar, longitudinal direction.*

Correlative Information for Figure 2.6.3.1.8

Product Form: Bar, 1-1/16-inch diameter

Properties:	TUS, ksi	TYS, ksi	Temp., F
	192	188	RT (unnotched)
	304	—	RT (notched)

Specimen Details: Notched, V-Groove, K_t = 3.0
0.283-inch gross diameter
0.200-inch net diameter
0.010-inch root radius, r
60° flank angle, ω

Surface Condition: Polished with abrasive nylon cord

Reference: 2.6.3.1.8

Test Parameters:

Loading – Axial
Frequency – 1800 cpm
Temperature – RT
Environment – Air

No. of Heats/Lots: 1

Equivalent Stress Equation:

$\log N_f = 9.64 - 3.21 \log (S_{eq} - 39.28)$
$S_{eq} = S_{max} (1-R)^{0.65}$
Standard Error of Estimate = 0.228
Standard Deviation in Life = 0.656
R^2 = 88%

Sample Size = 19

[Caution: The equivalent stress model may provide unrealistic life predictions for stress ratios beyond those represented above]

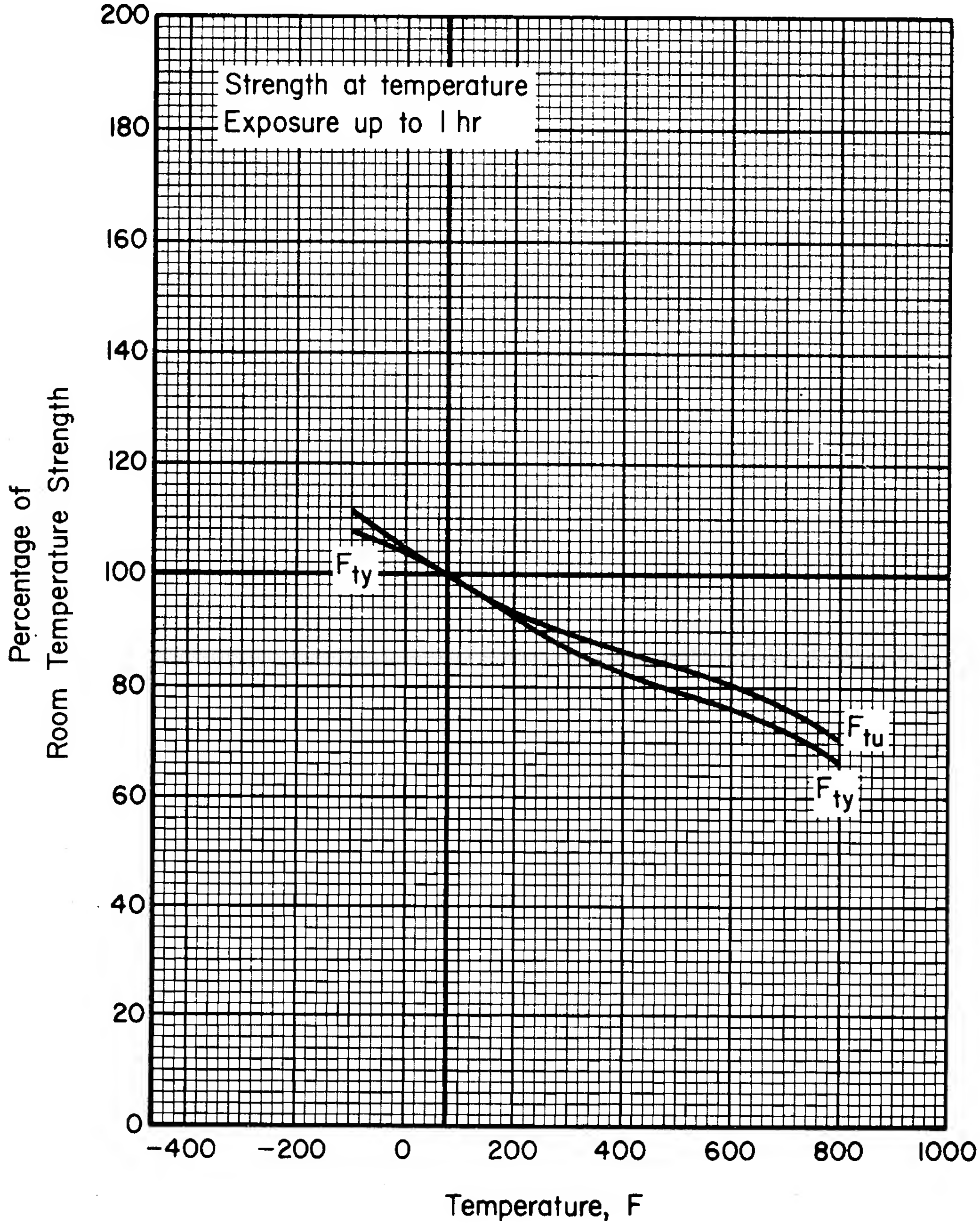

FIGURE 2.6.3.2.1. *Effect of temperature on the tensile ultimate strength (F_{tu}) and the tensile yield strength (F_{ty}) of Custom 450 (H1050) stainless steel bar.*

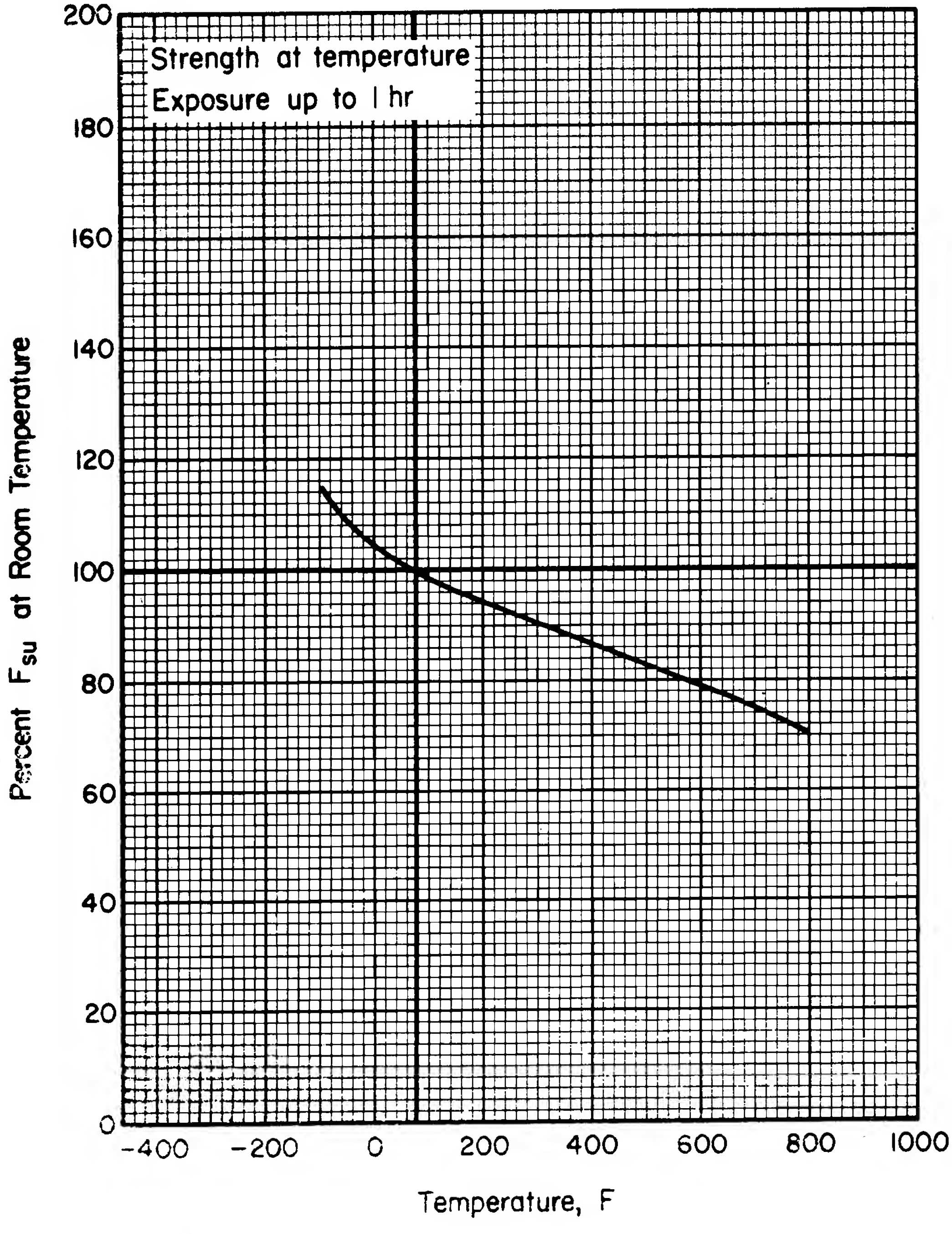

FIGURE 2.6.3.2.2. *Effect of temperature on the ultimate shear strength (F_{su}) of Custom 450 (H1050) stainless steel bar.*

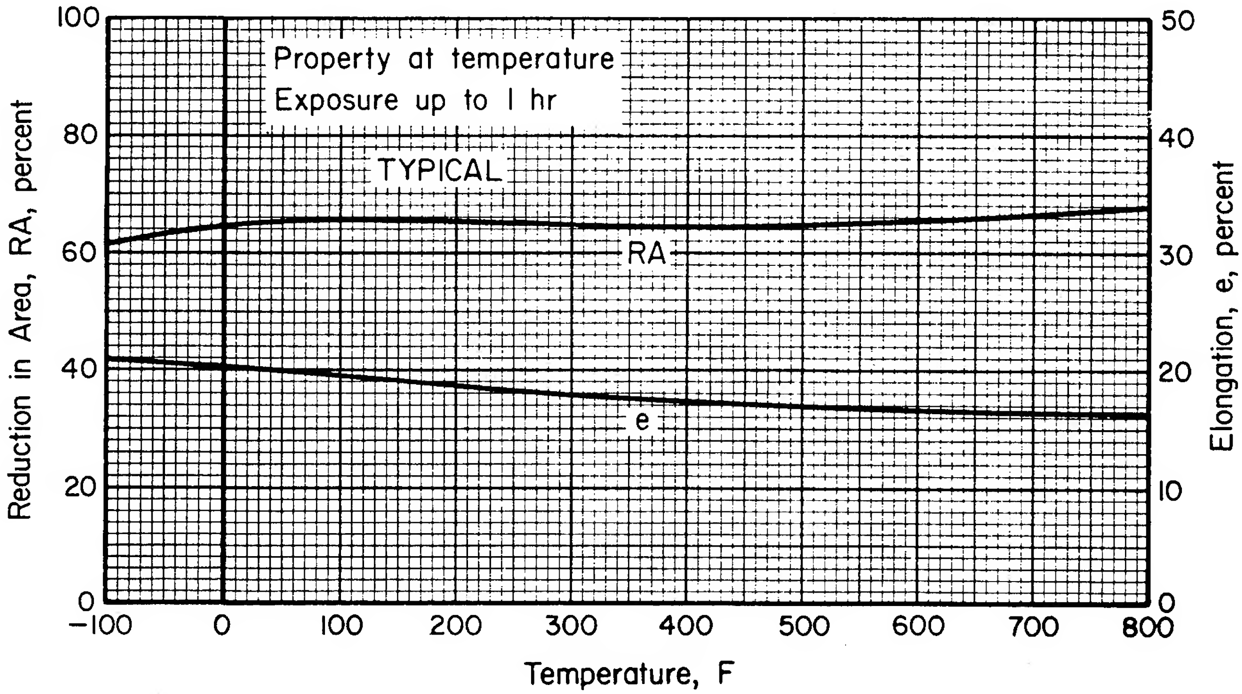

FIGURE 2.6.3.2.5. *Effect of temperature on the elongation (e) and the reduction of area (RA) of Custom 450 (H1050) stainless steel bar.*

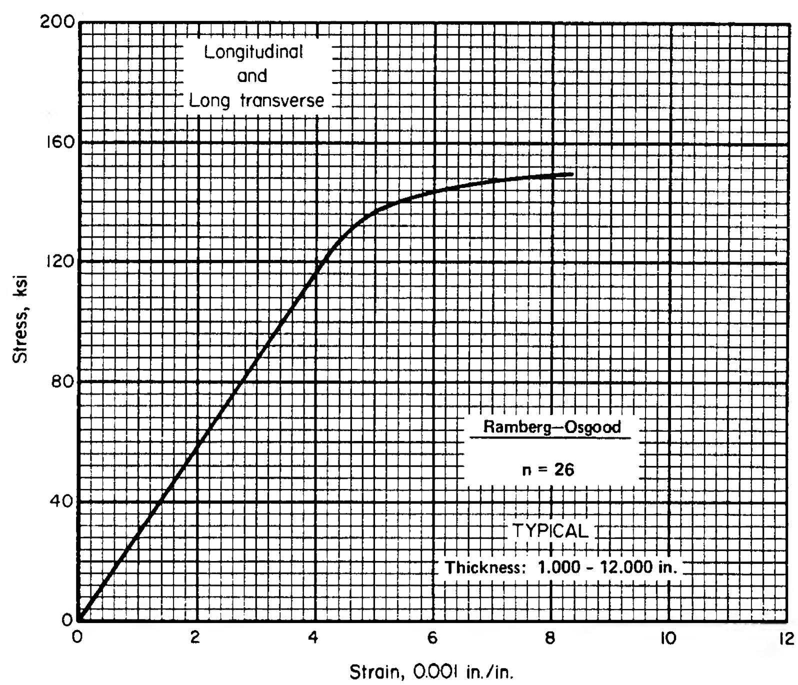

FIGURE 2.6.3.2.6. *Typical tensile stress-strain curve for Custom 450 (H1050) stainless steel bar at room temperature.*

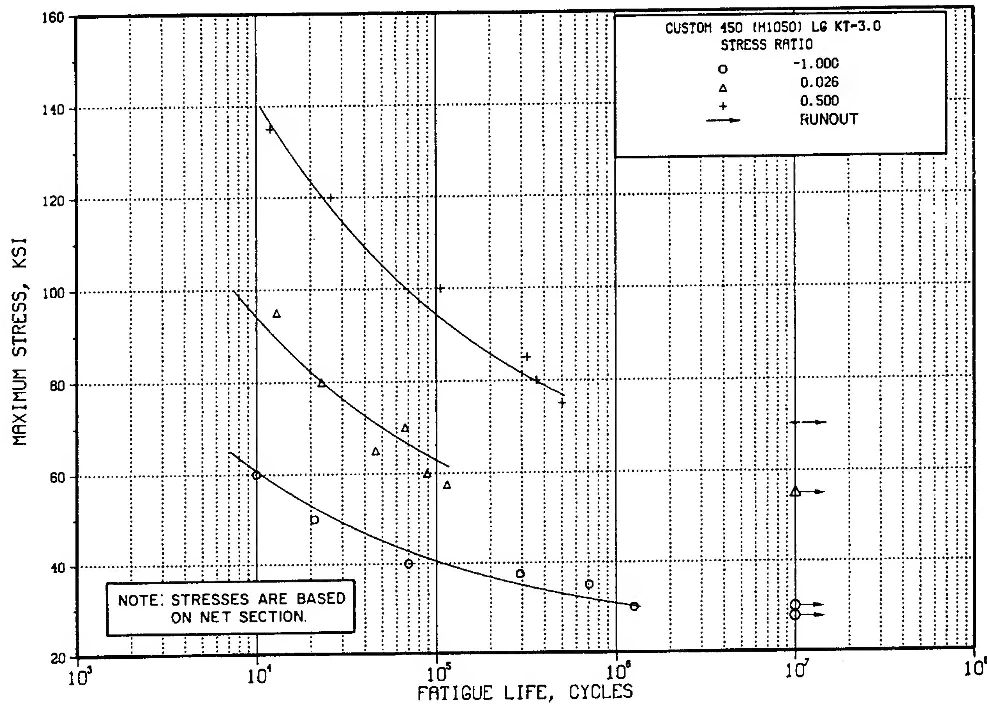

FIGURE 2.6.3.2.8. *Best-fit S/N curves for notched, K_t = 3.0 Custom 450 (H1050) stainless steel (ESR) bar, longitudinal direction.*

Correlative Information for Figure 2.6.3.2.8

Product Form: Bar, 1-1/16-inch diameter

Properties:	TUS, ksi	TYS, ksi	Temp., F
	156	151	RT (unnotched)
	244	—	RT (notched)

Specimen Details: Notched, V-Groove, K_t = 3.0
0.283-inch gross diameter
0.200-inch net diameter
0.010-inch root radius, r
60° flank angle, ω

Surface Condition: Polished with abrasive nylon cord

Reference: 2.6.3.1.8

Test Parameters:

Loading - Axial
Frequency - 1800 cpm
Temperature - RT
Environment - Air

No. of Heats/Lots: 1

Equivalent Stress Equation:

Log N_f = 9.59−3.15 log (S_{eq}−33.23)
$S_{eq} = S_{max}\,(1\text{-}R)^{0.607}$
Standard Error of Estimate = 0.188
Standard Deviation in Life = 0.649
R^2 = 92%

Sample Size = 18

[Caution: The equivalent stress model may provide unrealistic life predictions for stress ratios beyond those represented above]

2.6.4 CUSTOM 455

2.6.4.0 *Comments and Properties.*—Custom 455 is a precipitation hardenable stainless steel with a martensitic structure in both the solution annealed and hardened conditions. It is used for parts requiring corrosion resistance and high strength at temperatures up to 800 F. It is produced by consumable electrode remelting and is available in the form of forgings, billet, bar, wire, strip, and welded tubing.

Manufacturing Considerations.—Custom 455 is normally supplied and fabricated in the solution annealed condition. Forming, machining, and joining operations are similar to those employed for other precipitation hardening stainless steels. Optimum weld ductility is obtained by postweld solution annealing prior to aging.

Heat Treatment.—The alloy can be heat treated to several strength levels. Consult the applicable materials specification or MIL-H-6875 for specific procedures. The minimum recommended hardening temperature to produce the optimum combination of strength, fracture toughness, and stress corrosion cracking resistance is 950 F. Higher strength is attainable with the 900 F aging treatment but at a sacrifice of fracture toughness and stress corrosion cracking resistance. Like other precipitation hardening stainless steels the fracture toughness, and stress intensity below which stress corrosion cracking does not occur improve with increasing aging temperature within the range of 900 F to 1000 F.

Usually parts are aged directly from the as-supplied solution annealed condition. When this condition has been altered during processing by hot working, severe cold working, or welding, the parts should be resolution annealed prior to aging. A dimensional contraction of about 0.0009 in./in. should be expected with the 950 F aging treatment.

Environmental Considerations.—The general corrosion resistance of Custom 455 is about equivalent to that of AISI Type 430 stainless steel.

Hydrogen embrittlement tests in 5 percent by weight acid saturated with H_2S at room temperature show the same degree of susceptibility as other high strength martensitic stainless steels.

When stress corrosion cracking is of concern, one should use the highest aging temperature consistent with the strength properties required. The 900 F aging treatment should not be employed when stress corrosion cracking is a consideration. Consult the material producers literature for available stress corrosion data.

Like other precipitation hardening stainless steels, Custom 455 increases slightly in tensile strength and loses some toughness when exposed for long periods of time at temperatures around 700 F. For most applications, the loss in toughness which occurs is not detrimental to performance.

Specifications and Properties.—Material specifications for Custom 455 are presented in Table 2.6.4.0(a). The room-temperature mechanical properties of Custom 455 are presented in Table 2.6.4.0(b). Physical properties at elevated temperatures are presented in Figure 2.6.4.0.

TABLE 2.6.4.0(a). *Material Specifications for Custom 455 Stainless Steel*

Specification	Form
AMS 5578	Tubing (welded)
AMS 5617	Bar and forging

2.6.4.1 *H950 Condition.*—Elevated temperature curves are presented in Figure 2.6.4.1.1, 2.6.4.1.2, and 2.6.4.1.5. A tensile stress-strain curve at room temperature is shown in Figure 2.6.4.1.6. Fatigue data at room temperature are presented in Figure 2.6.4.1.8(a) and (b).

2.6.4.2 *H1000 Condition.*—Elevated temperature curves are shown in Figures 2.6.4.2.1, 2.6.4.2.2, and 2.6.4.2.5. A tensile stress-strain curve at room temperature is presented in Figure 2.6.4.2.6. Fatigue data at room temperature are shown in Figure 2.6.4.2.8.

TABLE 2.6.4.0(b). *Design Mechanical and Physical Properties of Custom 455 Stainless Steel*

Specification	AMS 5578		AMS 5617		
Form	Tubing (Welded)		Bar		
Condition	H950		H950		H1000
Thickness or diameter, in.[a]	0.020-0.062	>0.062	≤4.000	4.001-6.000	≤8.000
Basis	S	S	S	S	S
Mechanical Properties:					
F_{tu}, ksi:					
L	220	220	225	220	200
LT	...	...	225[b]	220[b]	...
ST	...	...	225[b]	220[b]	...
F_{ty}, ksi:					
L	205	205	210	205	185
LT	...	...	210[b]	205[b]	...
ST	...	...	210[b]	205[b]	...
F_{cy}, ksi:					
L	...	...	219	214	193
LT	...	...	219	214	193
ST	...	...	219	214	193
F_{su}, ksi	...	...	133	130	124
F_{bru}, ksi:					
(e/D = 1.5)	...	...	355	347	324
(e/D = 2.0)	...	...	450	440	409
F_{bry}, ksi:					
(e/D = 1.5)	...	...	311	303	285
(e/D = 2.0)	...	...	366	358	343
e, percent:					
L	3	4	10	10	10
LT	...	...	5[b]	5[b]	...
ST	...	...	5[b]	5[b]	...
RA, percent:					
L	...	...	40	40	40
LT	...	...	20[b]	20[b]	...
ST	...	...	20[b]	20[b]	...
E, 10^3 ksi	28.5				28.9
E_c, 10^3 ksi	30.0				30.0
G, 10^3 ksi	11.3				11.5
μ	0.27				0.26
Physical Properties:					
ω, lb/in.^{3}	0.28				
C, Btu/(lb)(F)	...				
K, Btu/[(hr)(ft^2)(F)/ft]	See Figure 2.6.4.0				
α, 10^{-6} in./in./F	See Figure 2.6.4.0				

[a]Wall thickness for tubing.
[b]For Grade 2 material only.

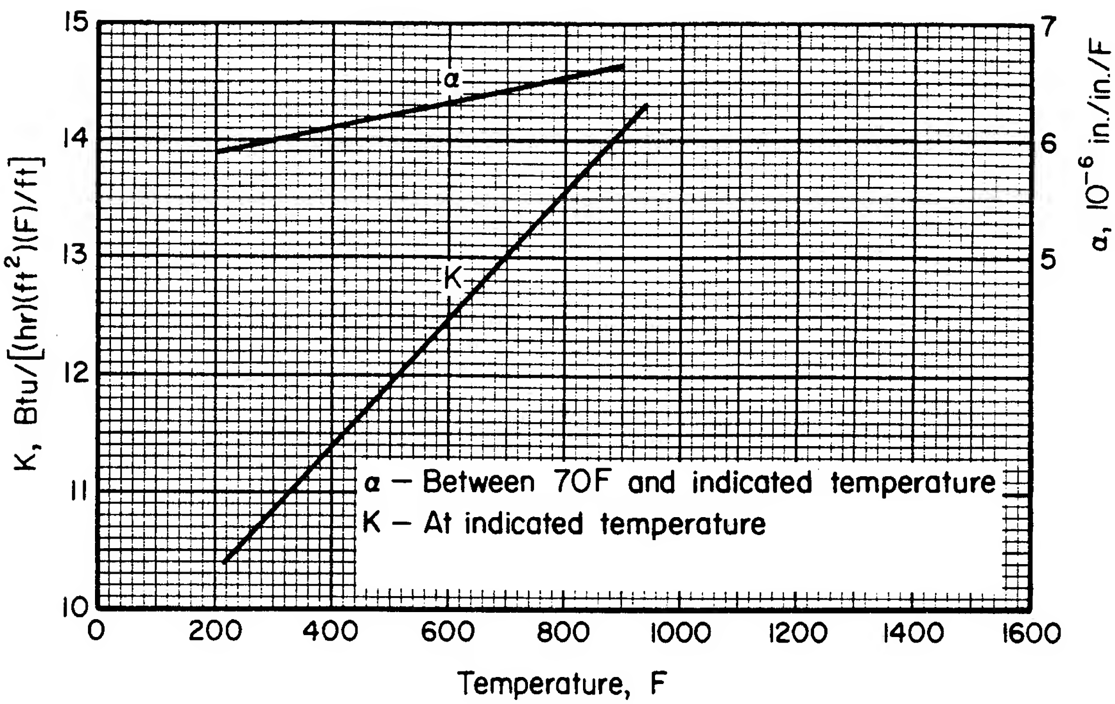

FIGURE 2.6.4.0 *Effect of temperature on the physical properties of Custom 455 (H950) stainless steel.*

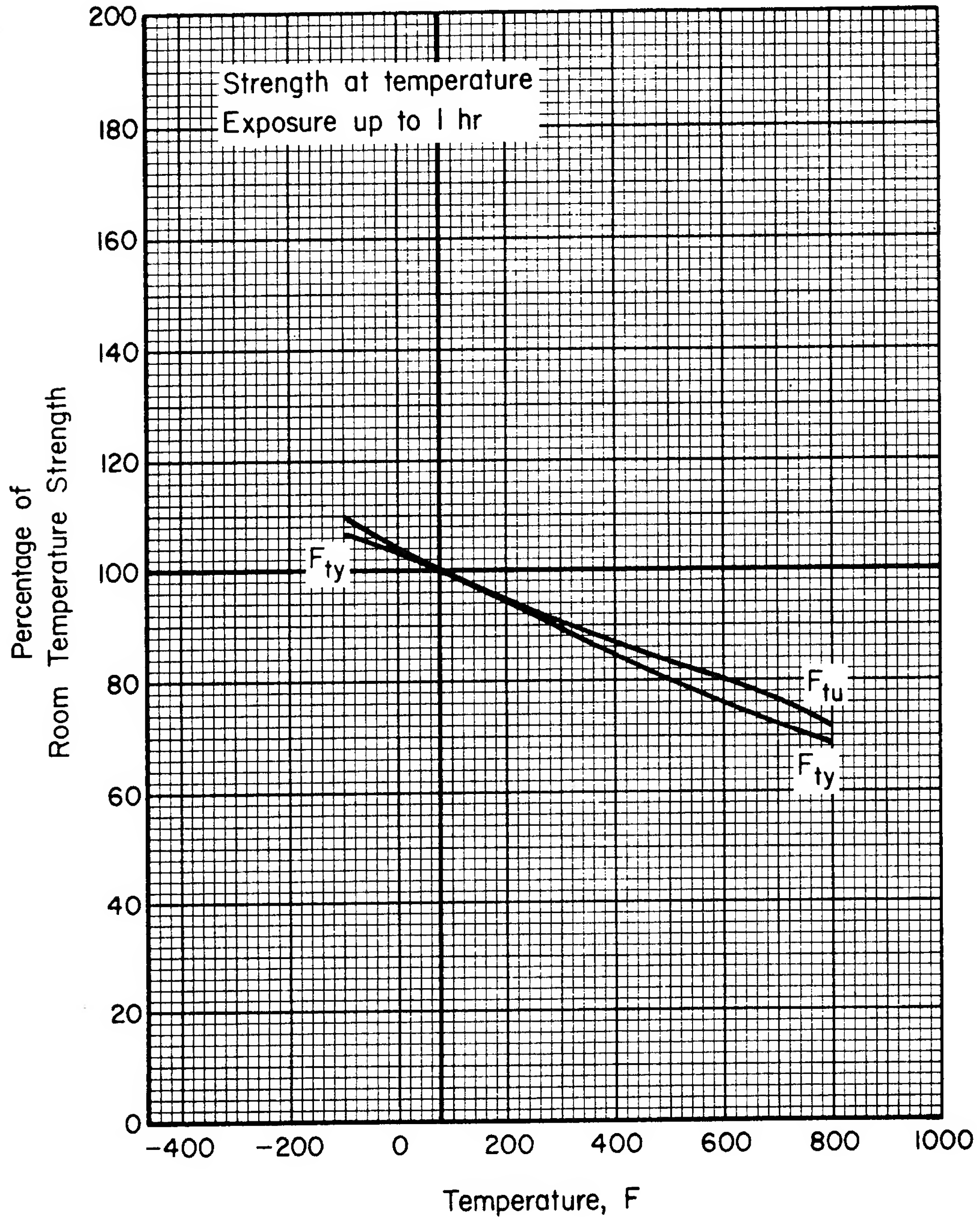

FIGURE 2.6.4.1.1. *Effect of temperature on the tensile ultimate strength (F_{tu}) and the tensile yield strength (F_{ty}) of Custom 455 (H950) stainless steel bar.*

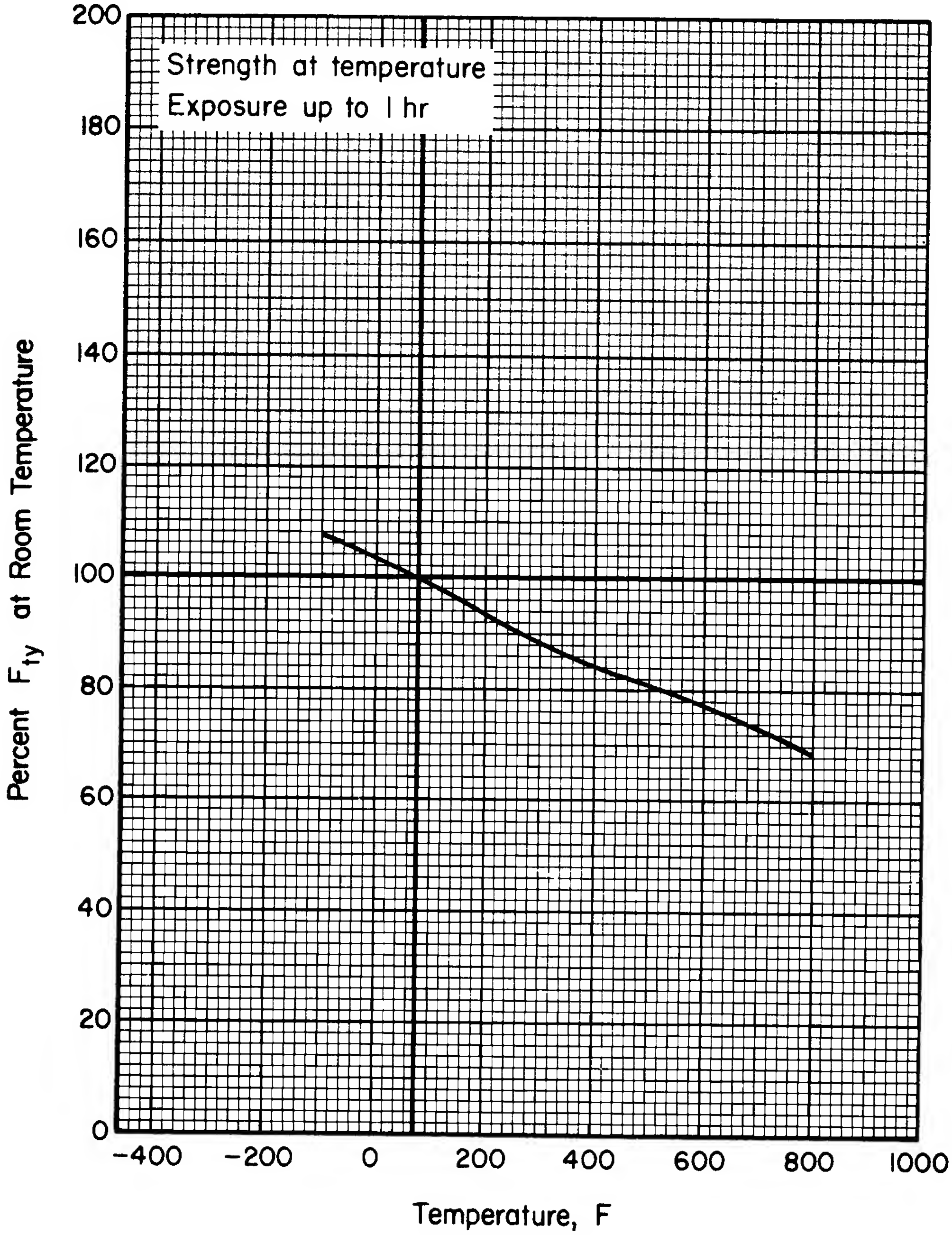

FIGURE 2.6.4.1.2. *Effect of temperature on the ultimate shear strength (F_{su}) of Custom 455 (H950) stainless steel bar.*

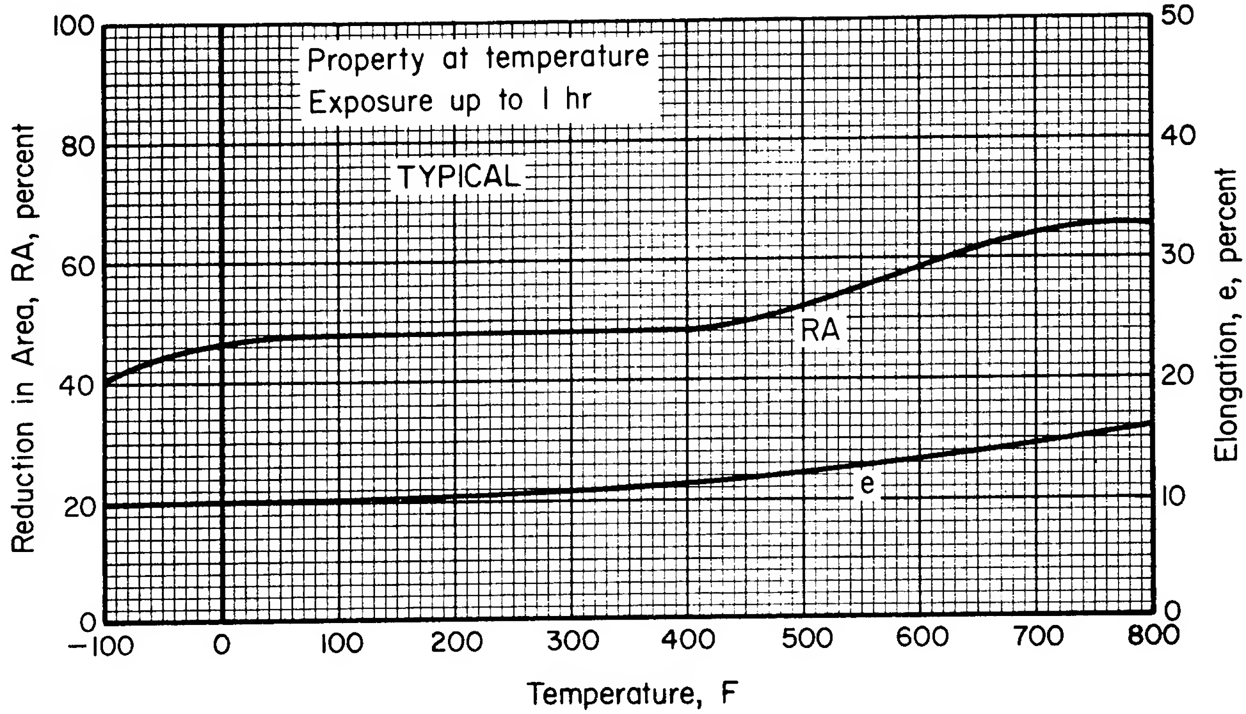

FIGURE 2.6.4.1.5. *Effect of temperature on the elongation (e) and reduction of area (RA) of Custom 455 (H950) stainless steel bar.*

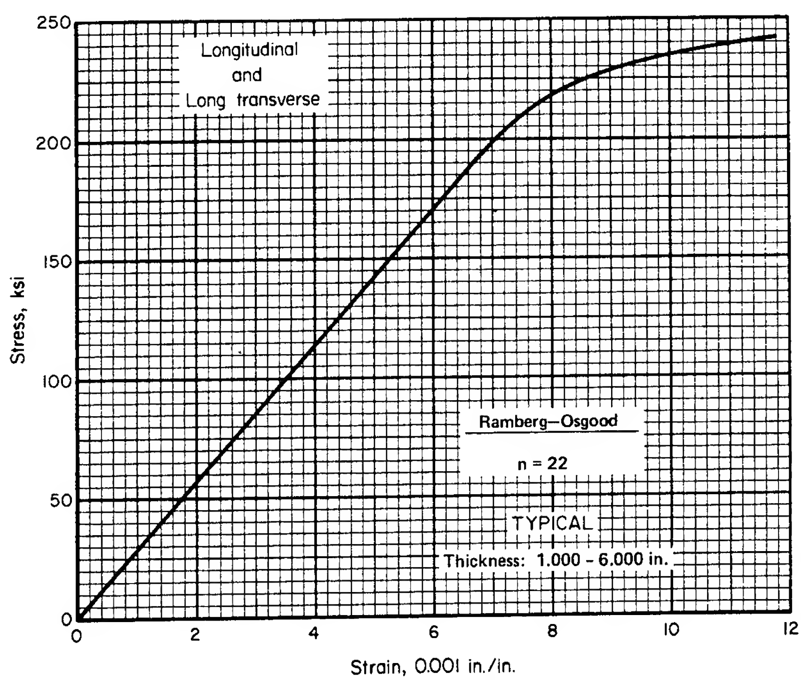

FIGURE 2.6.4.1.6. *Typical tensile stress-strain curve for Custom 455 (H950) stainless steel bar at room temperature.*

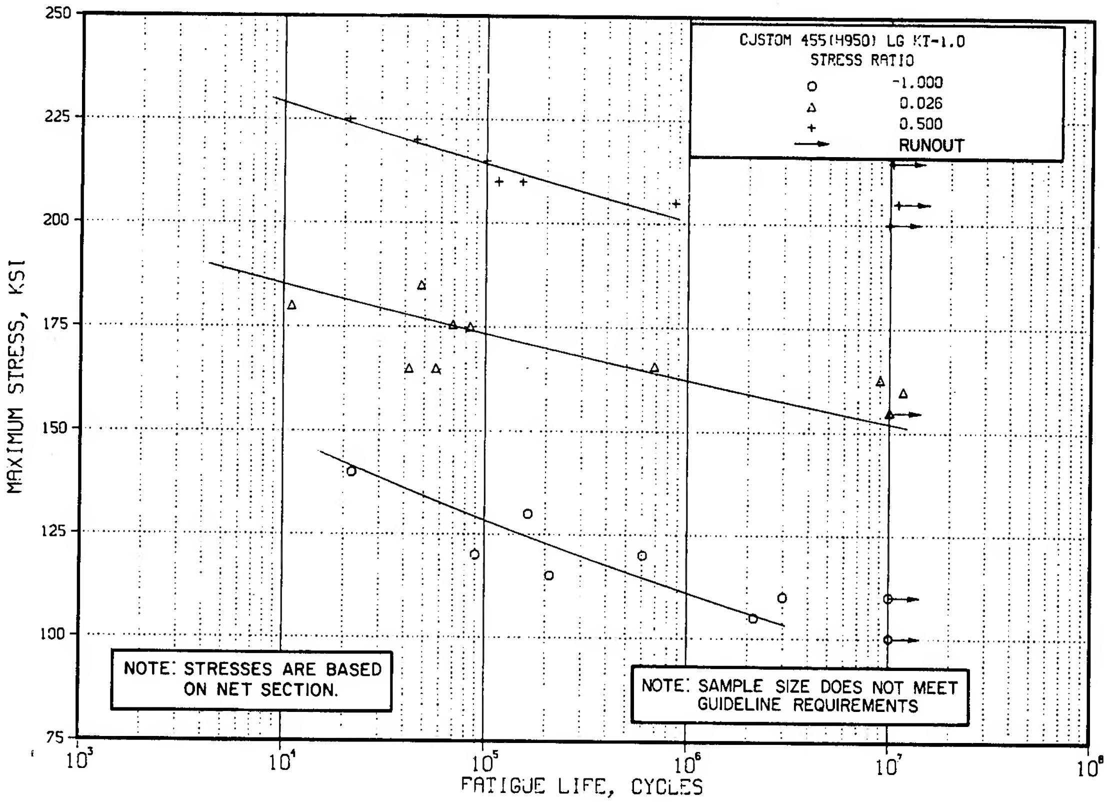

FIGURE 2.6.4.1.8(a). *Best-fit S/N curves for unnotched Custom 455 (H950) stainless steel bar, longitudinal direction.*

Correlative Information for Figure 2.6.4.1.8(a)

Product Form: Bar, 1-1/16-inch diameter

Properties:	TUS, ksi	TYS, ksi	Temp., F
	245	242	RT (unnotched)

Specimen Details: Unnotched
0.200-inch diameter

Surface Condition: Hand polished in longitudinal direction, finishing with 3μ diamond paste

Reference: 2.6.3.1.8

Test Parameters:

Loading - Axial
Frequency - 1800 cpm
Temperature - RT
Environment - Air

No. of Heats/Lots: 1

Maximum Stress Equations:

Log N_f = 38.1-15.7 log S_{max}, R = -1.0

= 82.9-34.8 log S_{max}, R = 0.026
= 85.9-34.7 log S_{max}, R = 0.50

Sample Size = 22

[Caution: The equivalent stress model may provide unrealistic life predictions for stress ratios beyond those represented above]

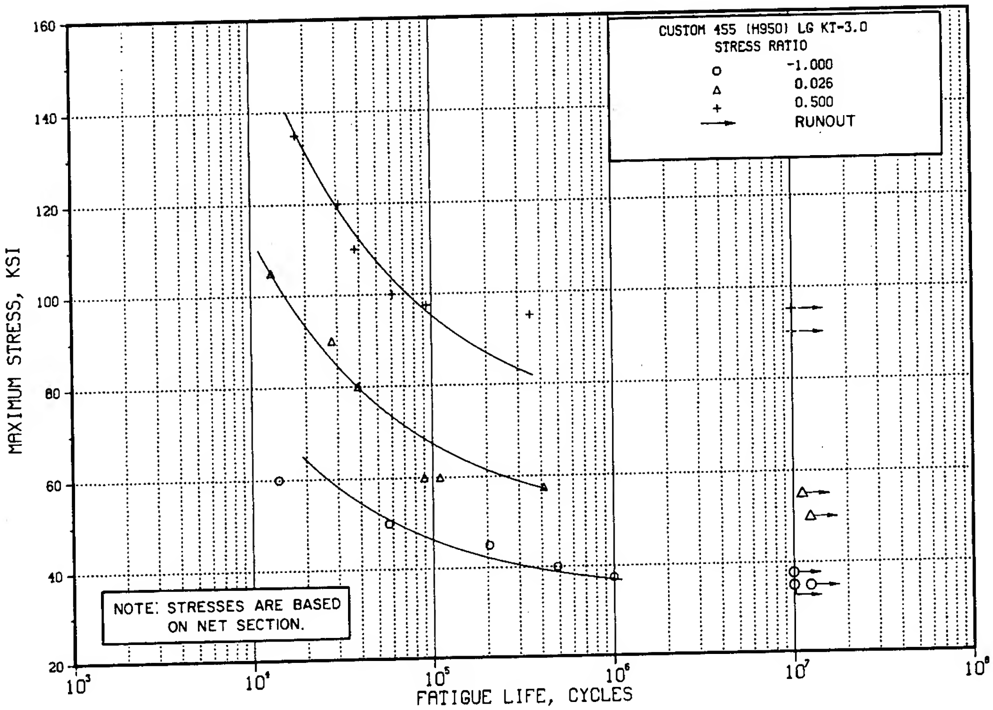

FIGURE 2.6.4.1.8(b). *Best-fit S/N curves for notched, K_t = 3.0, Custom 455 (H950) stainless steel bar, longitudinal direction.*

Correlative Information for Figure 2.6.4.1.8(b)

Product Form: Bar, 1-1/16-inch diameter

Properties:	TUS, ksi	TYS, ksi	Temp., F
	245	242	RT (unnotched)
	361	—	RT (notched)

Specimen Details: Notched, V-Groove, K_t = 3.0
0.283-inch gross diameter
0.200-inch net diameter
0.010-inch root radius, r
60° flank angle, ω

Surface Condition: Polished with abrasive nylon cord

Reference: 2.6.3.1.8

Test Parameters:

Loading – Axial
Frequency – 1800 cpm
Temperature – RT
Environment – Air

No. of Heats/Lots: 1

Equivalent Stress Equation:

$\log N_f = 7.42 - 1.90 \log (S_{eq} - 47.34)$
$S_{eq} = S_{max} (1-R)^{0.515}$
Standard Error of Estimate = 0.246
Standard Deviation in Life = 0.568
R^2 = 81%

Sample Size = 17

[Caution: The equivalent stress model may provide unrealistic life predictions for stress ratios beyond those represented above]

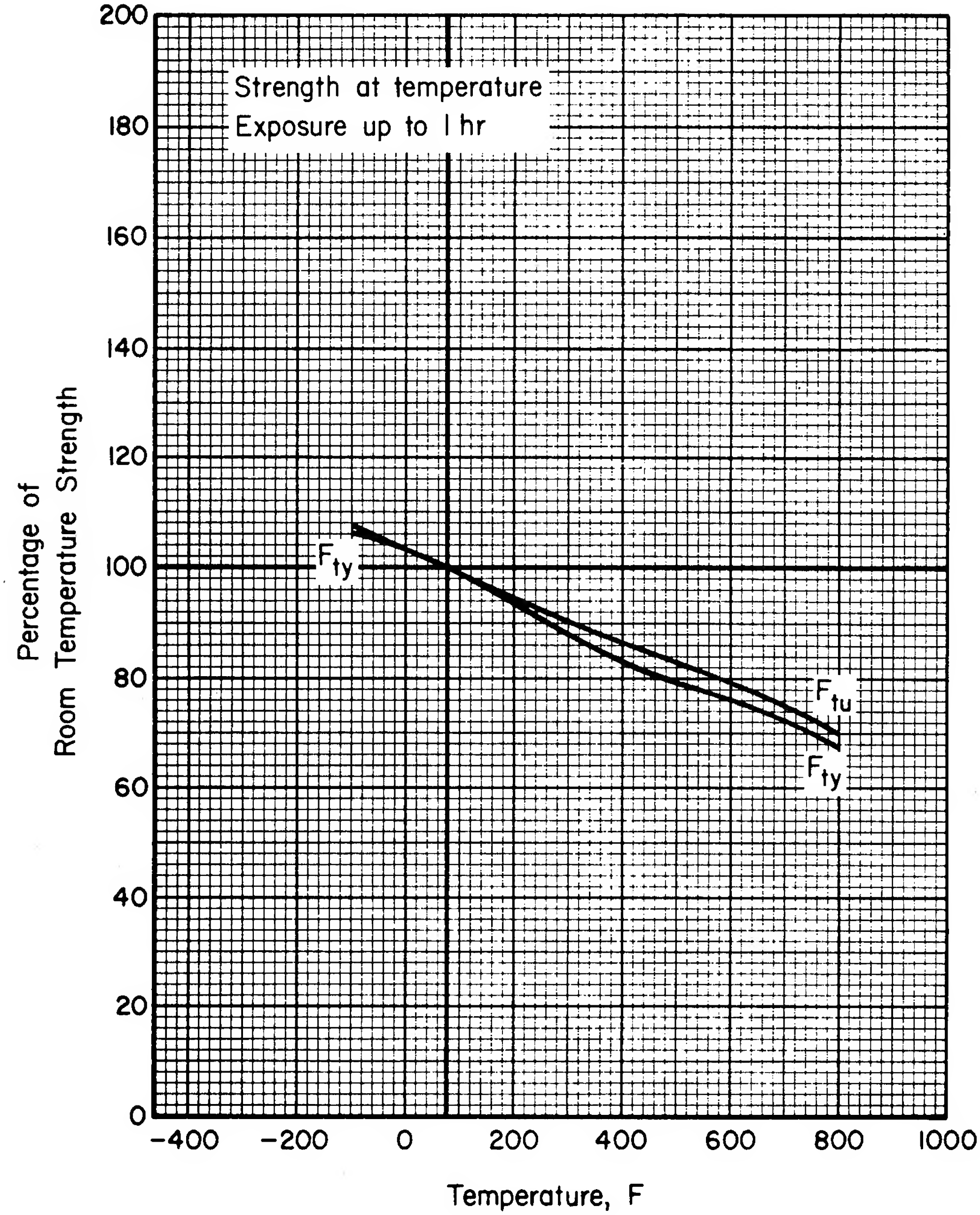

FIGURE 2.6.4.2.1. *Effect of temperature on the tensile ultimate strength (F_{tu}) and the tensile yield strength (F_{ty}) of Custom 455 (H1000) stainless steel bar.*

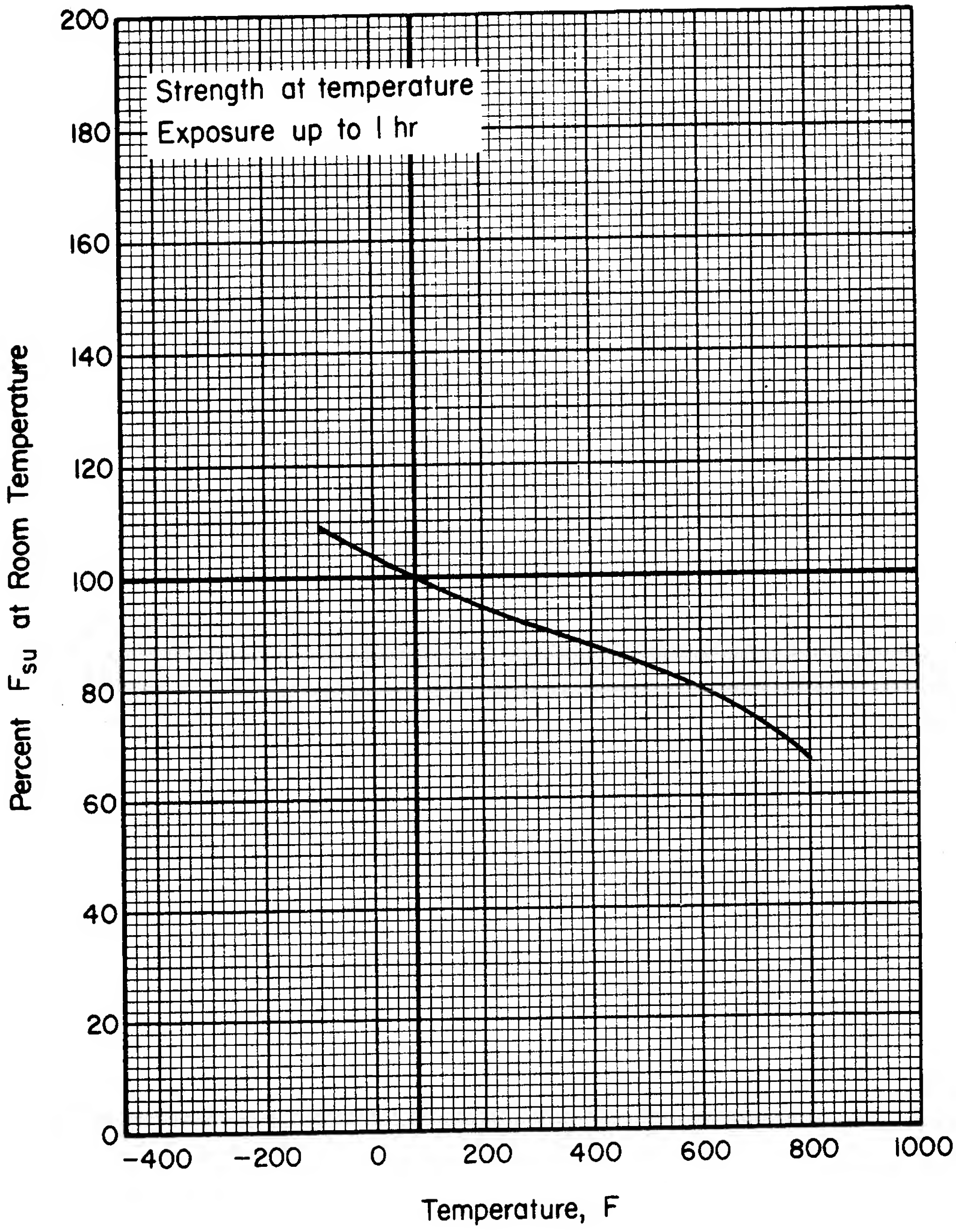

FIGURE 2.6.4.2.2. *Effect of temperature on the ultimate shear strength (F_{su}) of Custom 455 (H1000) stainless steel bar.*

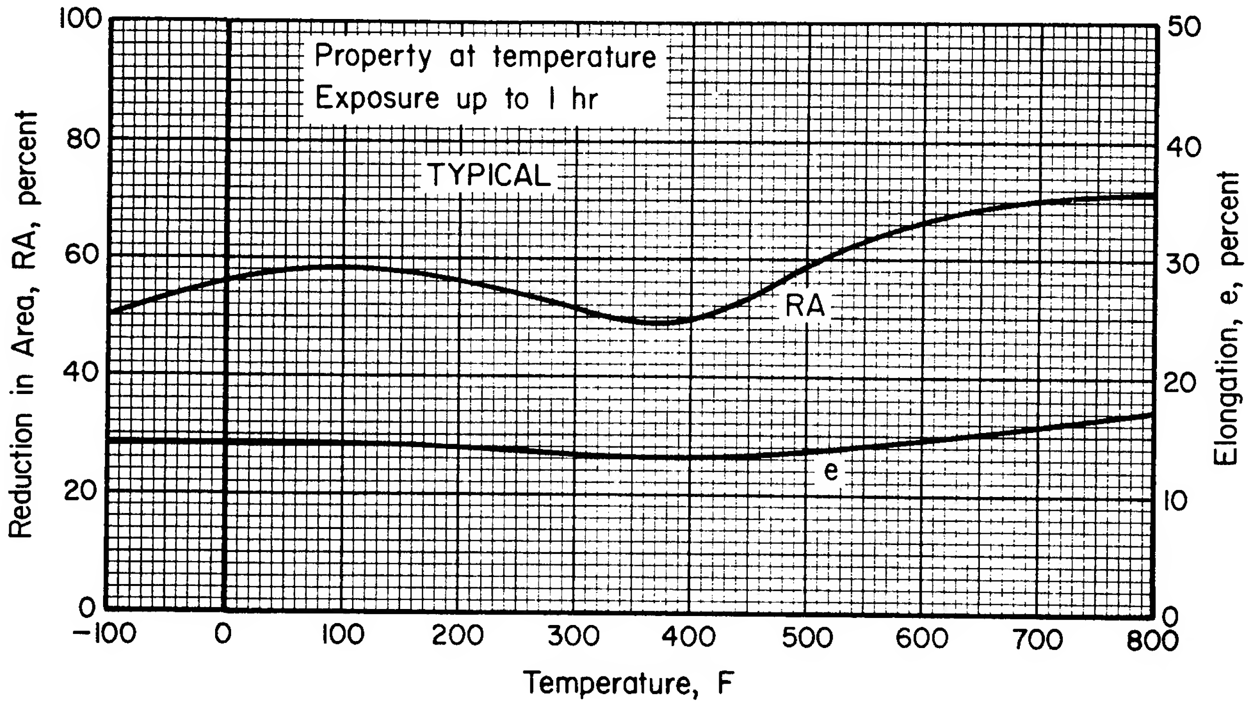

FIGURE 2.6.4.2.5. *Effect of temperature on the elongation (e) and the reduction of area (RA) of Custom 455 (H1000) stainless steel bar.*

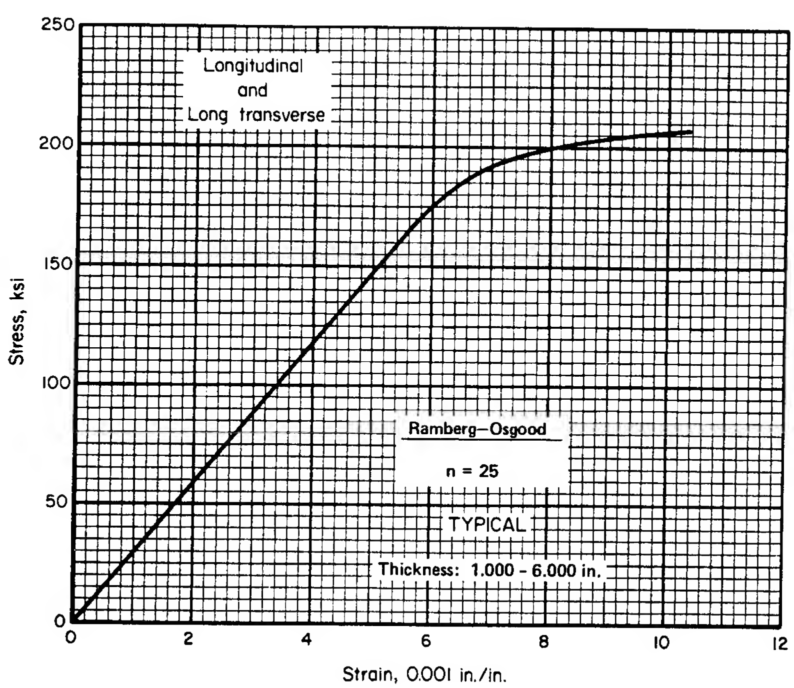

FIGURE 2.6.4.2.6. *Typical tensile stress-strain curve for Custom 455 (H1000) stainless steel bar at room temperature.*

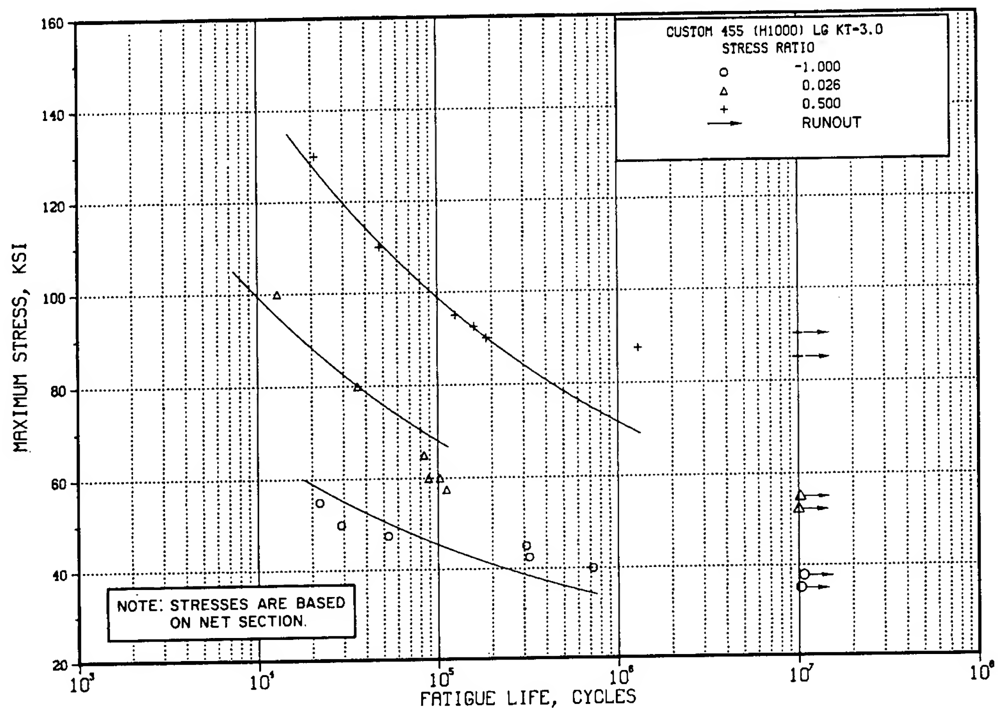

FIGURE 2.6.4.2.8. *Best-fit S/N curves for notched, K_t = 3.0 Custom 455 (H1000) stainless steel bar, longitudinal direction.*

Correlative Information for Figure 2.6.4.2.8

Product Form: Bar, 1-1/16-inch diameter

Properties:	TUS, ksi	TYS, ksi	Temp., F
	214	209	RT (unnotched)
	335	—	RT (notched)

Specimen Details: Notched, V-Groove, K_t = 3.0
0.283-inch gross diameter
0.200-inch net diameter
0.010-inch root radius, r
60° flank angle, ω

Surface Condition: Polished with abrasive nylon cord

Reference: 2.6.3.1.8

Test Parameters:

Loading – Axial
Frequency – 1800 cpm
Temperature – RT
Environment – Air

No. of Heats/Lots: 1

Equivalent Stress Equation:

Log N_f = 12.37–4.44 log (S_{eq}–21.43)
$S_{eq} = S_{max} (1\text{-}R)^{0.561}$
Standard Error of Estimate = 0.359
Standard Deviation in Life = 0.540
R^2 = 56%

Sample Size = 18

[Caution: The equivalent stress model may provide unrealistic life predictions for stress ratios beyond those represented above]

2.6.5 PH13-8Mo

2.6.5.0 *Comments and Properties.*—PH13-8Mo is a martensitic precipitation-hardening stainless steel used for parts requiring corrosion resistance, high strength, high fracture toughness, and oxidation resistance up to 800 F. When used at temperatures between 600 and 800 F, some loss in notch toughness will occur. The loss is time-temperature dependent and will occur gradually over thousands of hours at 600 F and hundreds of hours at 800 F. Depending upon the application, this loss in notch toughness may not be important and useful engineering properties may still be available. Good transverse mechanical properties are one of the major advantages of PH 13-8Mo. PH 13-8Mo is produced by double vacuum melting and is available in the form of forgings, plate, bar, and wire, normally furnished in the solution-treated (A) condition.

Manufacturing Considerations.—Forming, joining, and machining operations are usually performed on material in Condition A, using similar procedures and equipment to those employed for other precipitation-hardening stainless steels. Best machinability is exhibited by Conditions H1150 and H1150M. A dimensional contraction of 0.0004 to 0.0006 and 0.0008 to 0.0012 in./in. occurs upon hardening to the H1000 and H1100 conditions, respectively.

Heat Treatment.—PH 13-8Mo must be used in the heat-treated condition and should not be placed in service in Condition A. The alloy can be heat treated to various strength levels having a wide range of properties. Consult the applicable material specification or MIL-H-6875 for specific heat treatment procedures.

Environmental Considerations.—PH13-8Mo is nearly equal to 17-4PH in general corrosion resistance and surpasses the other hardenable stainless steels in stress-corrosion resistance. However, for tensile application where stress corrosion is a possibility, PH13-8Mo should be aged at the highest temperature compatible with strength requirements and at a temperature not lower than 1000 F for 4 hours minimum aging time.

Specification and Properties.—A material specification for PH13-8Mo is presented in Table 2.6.5.0(a). The room-temperature mechanical and physical properties for PH13-8Mo are presented in Table 2.6.5.0(b) and (c). The physical properties of this alloy at elevated temperatures are presented in Figure 2.6.5.0.

TABLE 2.6.5.0(a). *Material Specification for PH13-8Mo Stainless Steel*

Specification	Form
AMS 5629	Bar, forging, ring, and extrusion (VIM plus CEVM)

2.6.5.1 *H950 and H1000 Conditions.*—Elevated temperature curves for tensile yield and ultimate strengths are presented in Figure 2.6.5.1.1. Typical tensile and compressive stress-strain and tangent-modulus curves for the H1000 condition at room temperature are depicted in Figures 2.6.5.1.6(a) and (b). Figure 2.6.5.1.6(c) contains typical full-range stress-strain curves at room temperature for various heat-treated conditions. Unnotched and notched fatigue information for H1000 condition at room temperature is presented in Figures 2.6.5.1.8(a) through (c).

TABLE 2.6.5.0(b). *Design Mechanical and Physical Properties of PH13-8Mo Stainless Steel*

Specification	AMS 5629							
Form	Round, hex, square and flat bar							
Condition	H950		H1000		H1025	H1050	H1100	H1150
Thickness or diameter, in.	<9.0		<8.0		≤12.0			
Basis	A	B	A	B	S	S	S	S
Mechanical Properties:[b]								
F_{tu}, ksi:								
L	217	221	201	208	185	175	150	135
T	217	221	201	208	185	175	150	135
F_{ty}, ksi:								
L	198	205	190[a]	200	175	165	135	90
T	198	205	190[a]	200	175	165	135	90
F_{cy}, ksi:								
L	...	...	200	211	...	...	...	...
T	...	...	200	211	...	...	...	...
F_{su}, ksi	...	...	117	122	...	...	...	...
F_{bru}, ksi:								
(e/D = 1.5)	...	...	302	313	...	...	...	...
(e/D = 2.0)	...	...	402	416	...	...	...	...
F_{bry}, ksi:								
(e/D = 1.5)	...	...	263	277	...	...	...	...
(e/D = 2.0)	...	...	338	356	...	...	...	...
e, percent (S-basis):								
L	10	...	10	...	11	12	14	14
T	10	...	10	...	11	12	14	14
RA, percent (S-basis):								
L	45	...	50	...	50	50	50	50
T	35	...	40	...	45	45	50	50
E, 10^3 ksi	28.3							
E_c, 10^3 ksi	29.4							
G, 10^3 ksi	11.0							
μ	0.28							
Physical Properties:								
ω, lb/in.^{3}	0.279							
C, Btu/(lb)(F)	0.11 (32 to 212 F) (Est.)							
K, and α	See Figure 2.6.5.0							

[a] S-basis. A value = 193 ksi.
[b] Design allowables were based mainly upon data from samples of material, supplied in the solution treated condition, which were aged to demonstrate response to heat treatment by suppliers.

TABLE 2.6.5.0(c). *Design Mechanical and Physical Properties of PH13-8Mo Stainless Steel*

Specification	AMS 5629					
Form	Forging, flash welded ring, and extrusion					
Condition	H950	H1000	H1025	H1050	H1100	H1150
Thickness or diameter, in.	≤12					
Basis	S	S	S	S	S	S
Mechanical Properties:						
F_{tu}, ksi:						
L	220	205	185	175	150	135
T	220	205	185	175	150	135
F_{ty}, ksi:						
L	205	190	175	165	135	90
T	205	190	175	165	135	90
F_{cy}, ksi:						
L	...	...	...	...	...	...
T	...	...	...	...	...	...
F_{su}, ksi	...	...	...	...	...	...
F_{bru}, ksi:						
(e/D = 1.5)	...	...	...	...	...	...
(e/D = 2.0)	...	...	...	...	...	...
F_{bry}, ksi:						
(e/D = 1.5)	...	...	...	...	...	...
(e/D = 2.0)	...	...	...	...	...	...
e, percent:						
L	10	10	11	12	14	14
T	10	10	11	12	14	14
RA, percent:						
L	45	50	50	50	50	50
T	35	40	45	45	50	50
E, 10^3 ksi	28.3					
E_c 10^3 ksi	29.4					
G, 10^3 ksi	11.0					
μ	0.28					
Physical Properties:						
ω, lb/in.^{3}	0.279					
C, Btu/(lb)(F)	0.11 (32 to 212 F) (Est.)					
K and α	See Figure 2.6.5.0					

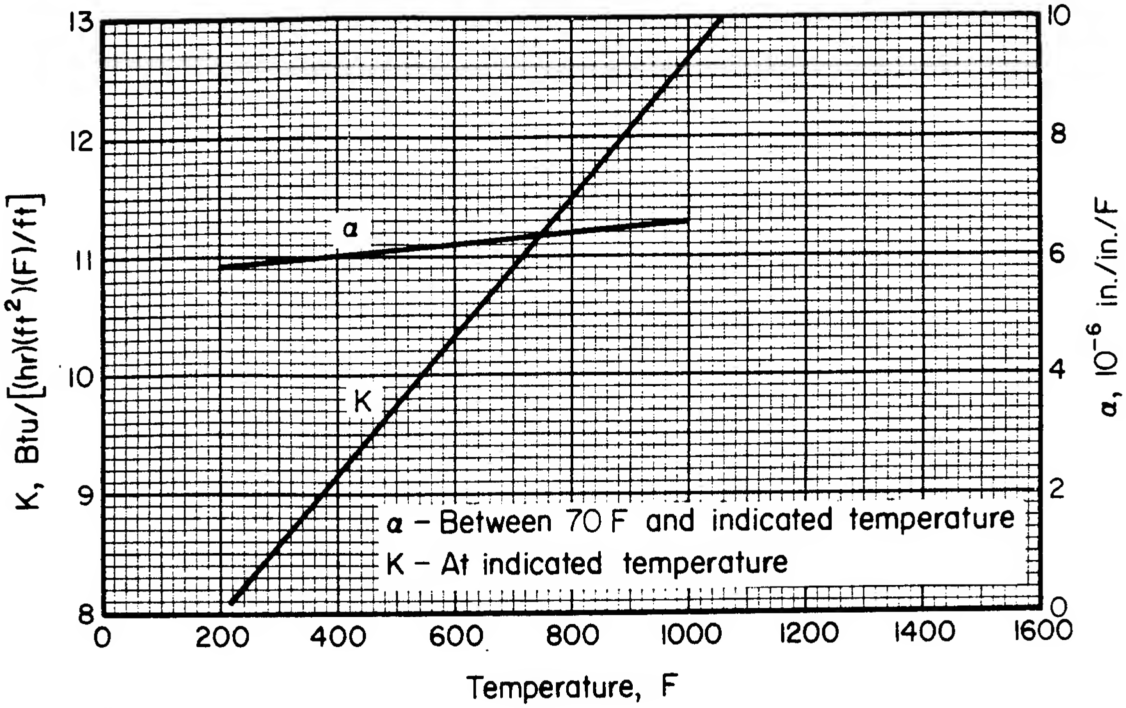

FIGURE 2.6.5.0 *Effect of temperature on the physical properties of PH13-8Mo stainless steel.*

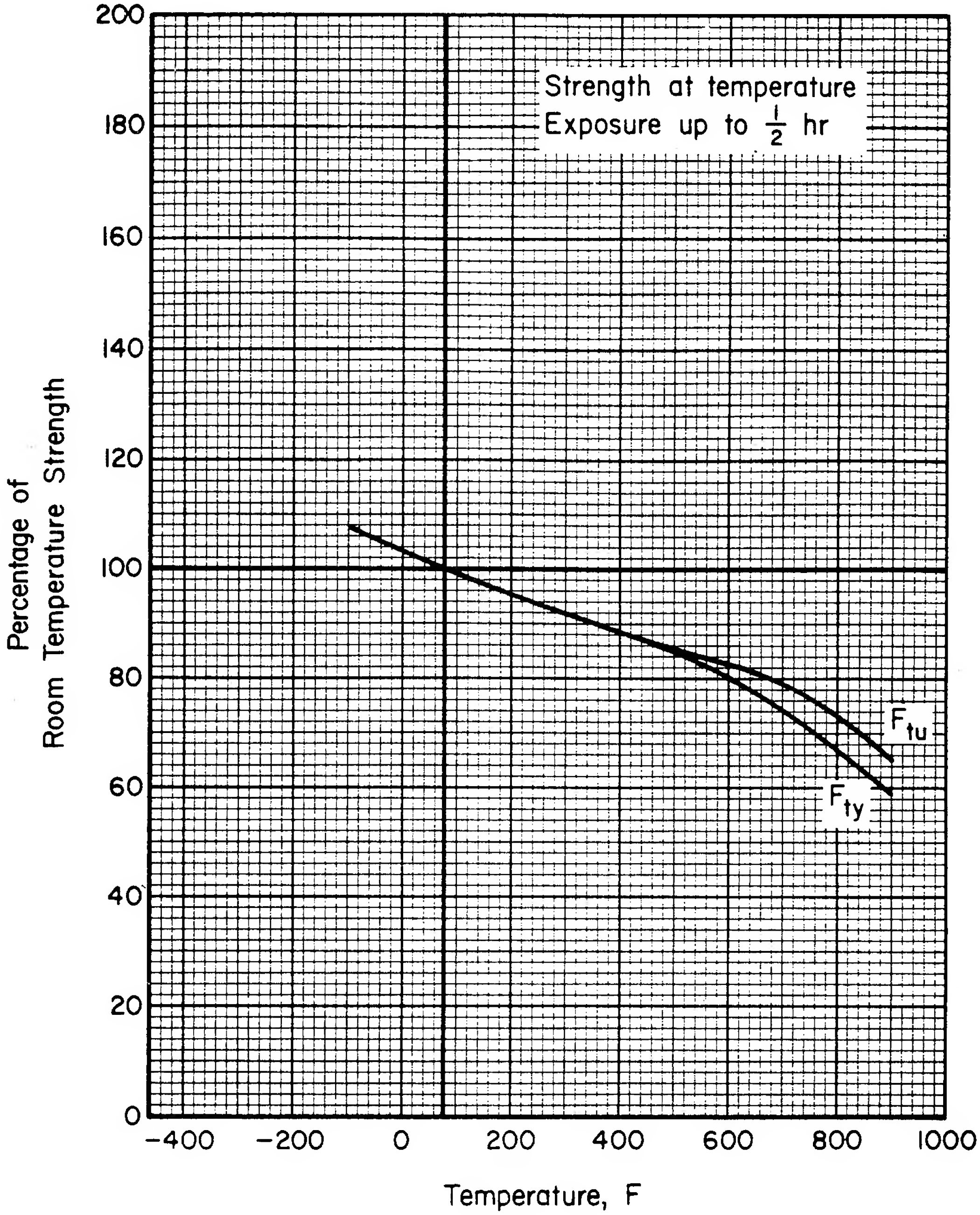

FIGURE 2.6.5.1.1. *Effect of temperature on the tensile ultimate strength (F_{tu}) and the tensile yield strength (F_{ty}) of PH13-8Mo (H950 and H1000) stainless steel bar.*

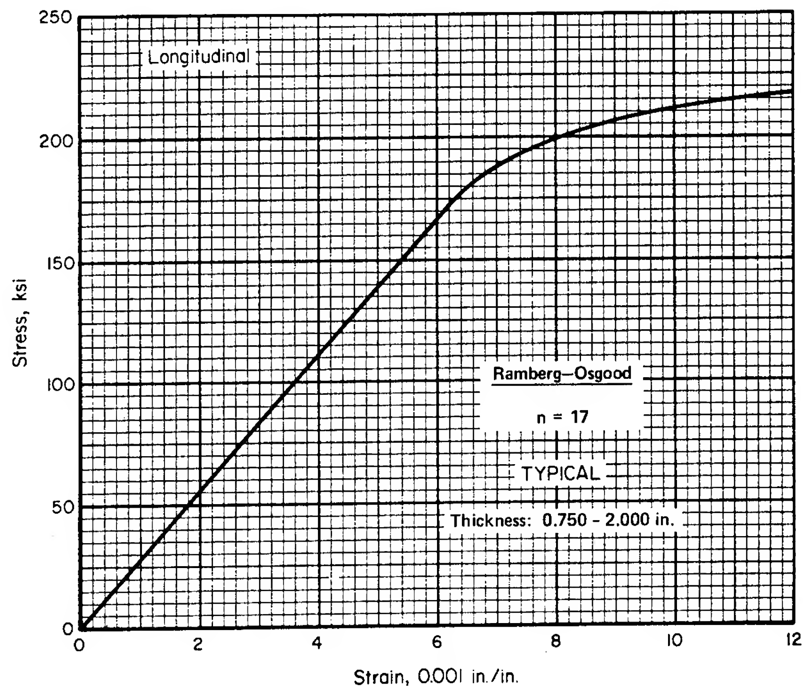

FIGURE 2.6.5.1.6(a). *Typical tensile stress-strain curve at room temperature for PH13-8Mo (H1000) stainless steel bar.*

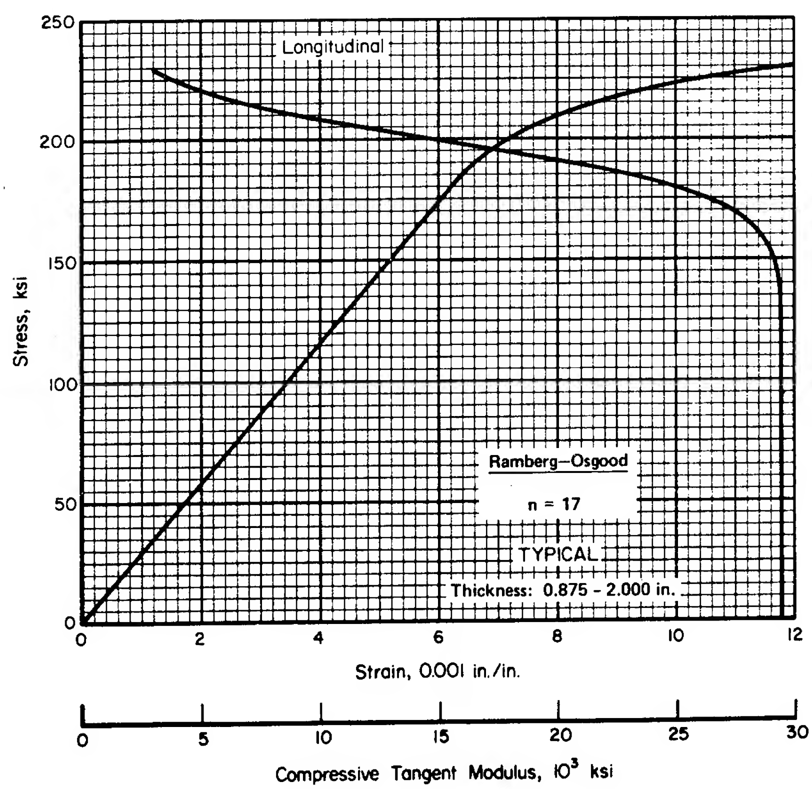

FIGURE 2.6.5.1.6(b). *Typical compressive stress-strain and compressive tangent-modulus curves at room temperature for PH13-8Mo (H1000) stainless steel bar.*

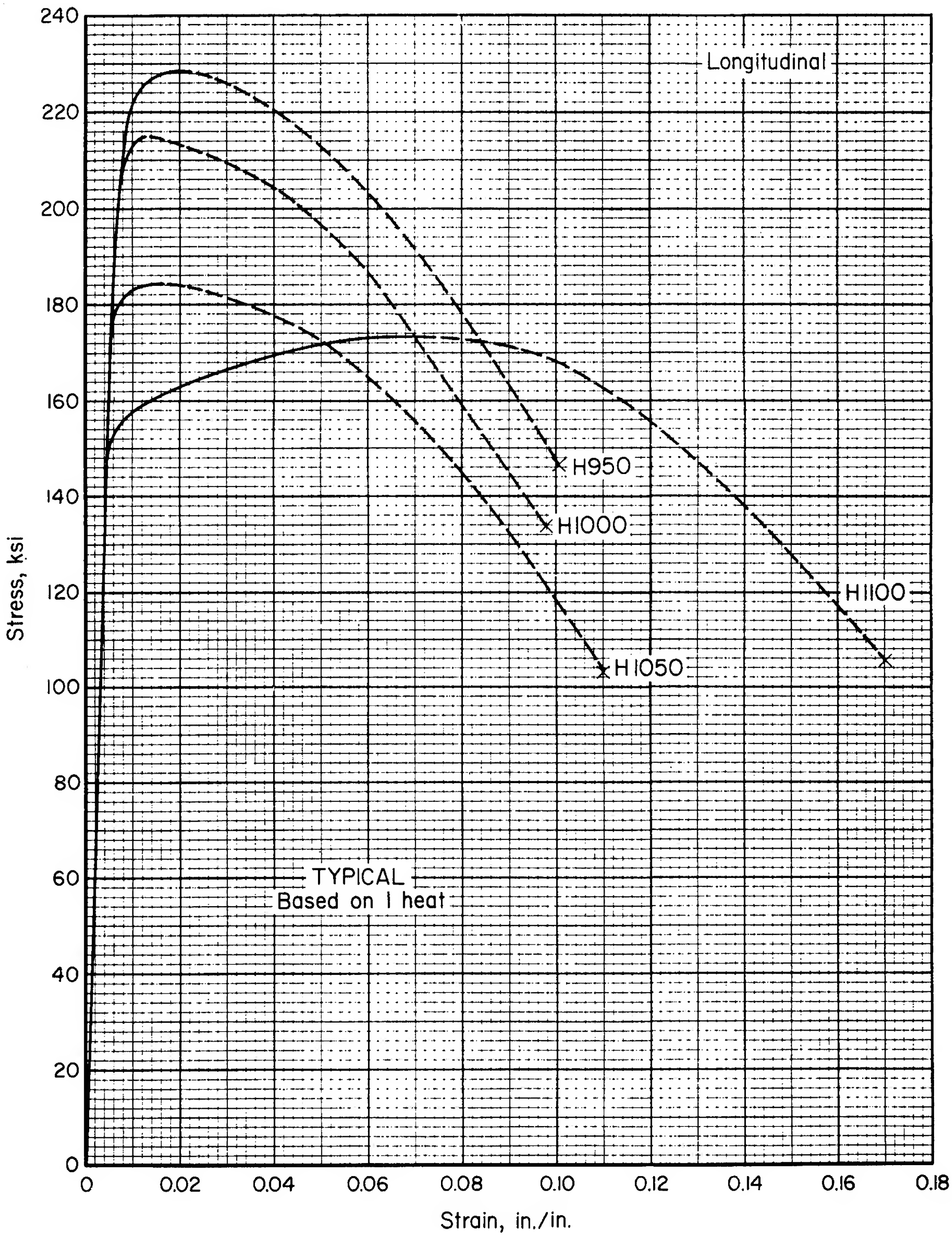

FIGURE 2.6.5.1.6(c). *Typical tensile stress-strain curves (full range) at room temperature for various heat treated conditions of PH13-8Mo stainless steel bar.*

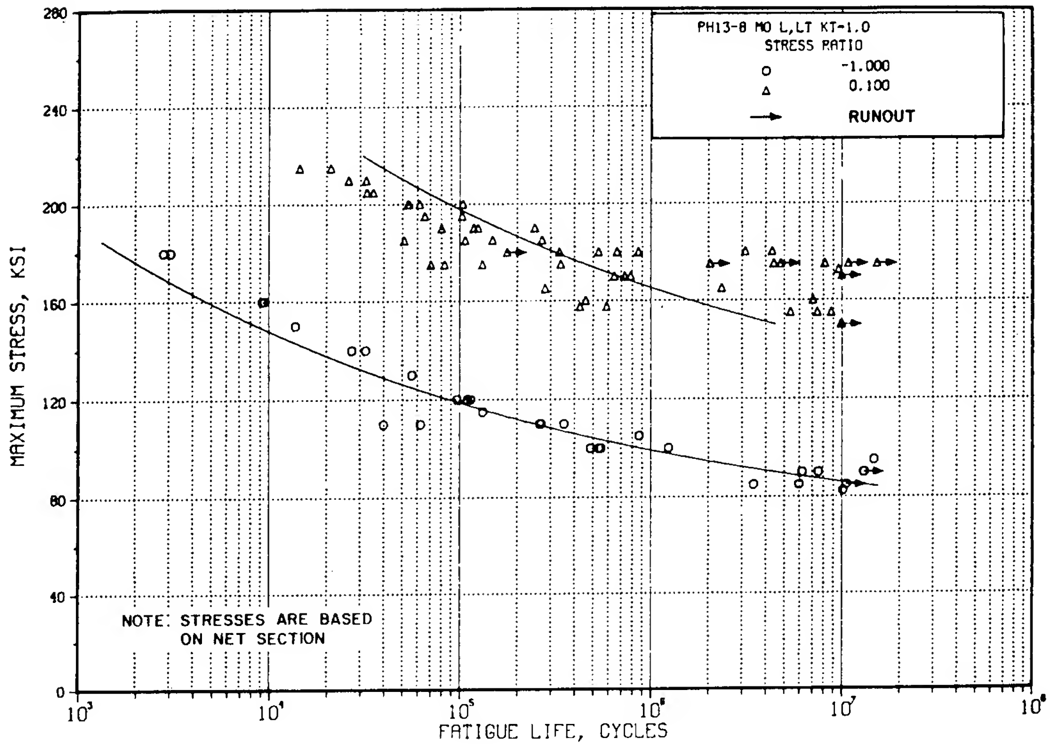

FIGURE 2.6.5.1.8(a). *Best-fit S/N curves for unnotched PH13-8Mo (H1000) forged bar, longitudinal and transverse directions.*

Correlative Information for Figure 2.6.5.1.8(a)

Product Form: Forged bar, 4 x 5 and 2 x 6 inches

Properties:	TUS, ksi	TYS, ksi	Temp., F
	205	197	RT

Specimen Details: Unnotched

Gross Diameter	Net Diameter
0.50	0.25
0.75	0.25

Surface Condition: Polished to RMS 10

References: 2.6.5.1.8(a), (b), (d)

Test Parameters:

Loading – Axial
Frequency – Not specified
Temperature – RT
Environment – Air

No. of Heats/Lots: 4

Equivalent Stress Equation:

$\log N_f = 16.32 - 5.75 \log (S_{eq} - 92.6)$
$S_{eq} = S_{max} (1-R)^{0.64}$
Standard Error of Estimate = 0.461
Standard Deviation in Life = 0.919
$R^2 = 75\%$

Sample Size = 86

[Caution: The equivalent stress model may provide unrealistic life predictions for stress ratios beyond those represented above]

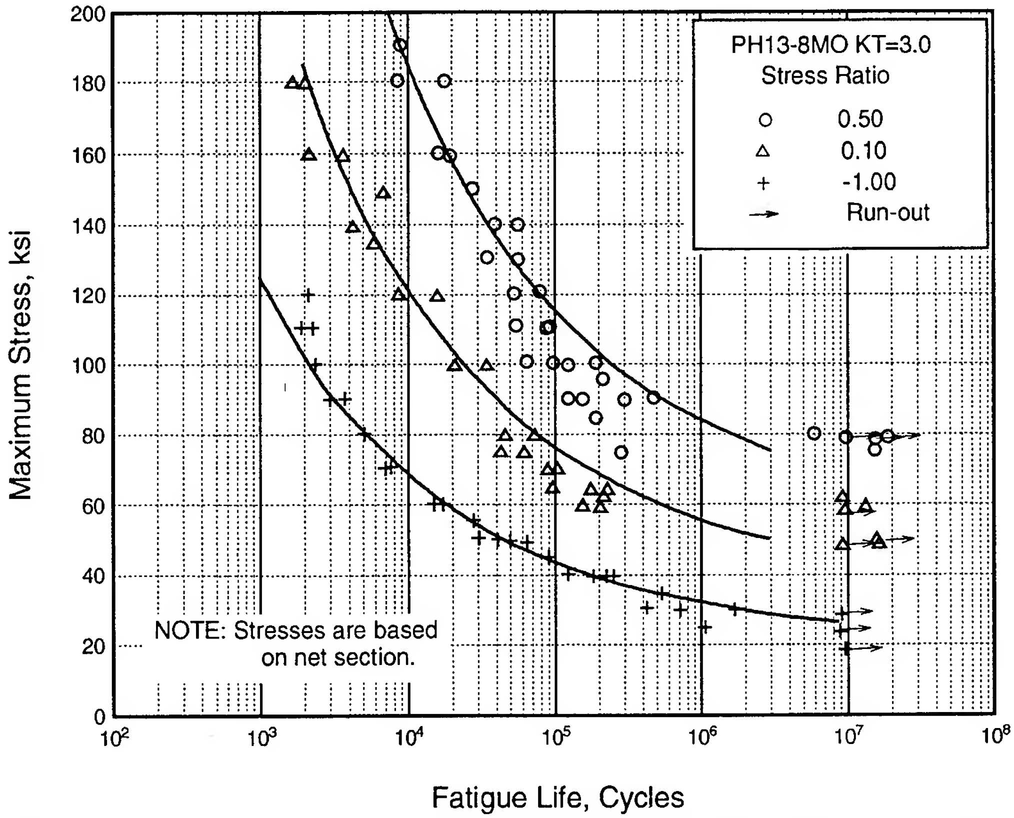

FIGURE 2.6.5.1.8(b). *Best-fit S/N curves for notched, K_t=3.0, PH13-8Mo (H1000) forged bar, longitudinal and long transverse directions.*

Correlative Information for Figure 2.6.5.1.8(b)

Product Form: Forged bar, 4 x 5 and 2 x 6 inches

Properties:

TUS, ksi	TYS, ksi	Temp., F
205	197	RT

Specimen Details: Notched, K_t=3.0

Gross Diameter	Net Diameter	Notch Root Radius
0.750	0.252	0.013
0.500	0.250	0.013

60 degree flank angle

Surface Condition: Notch was polished with abrasively charged wire and rotating wire with oil and alundum grit

References: 2.6.5.1.8(a), (b), (d)

Test Parameters
Loading - Axial
Frequency - Not Specified
Temperature - RT
Environment - Air

No. of Heats/Lots: 4

Equivalent Stress Equation
$\text{Log } N_f = 9.90 - 3.13 \log (S_{eq} - 34.4)$
$S_{eq} = S_{max} (1 - R)^{0.68}$
Standard Deviation of Log (Life) = 23.1 ($1/S_{eq}$)
Adjusted R^2 Statistic = 92%

Sample Size: 104

[Caution: The equivalent stress model may provide unrealistic life predictions for stress ratios beyond those represented above.]

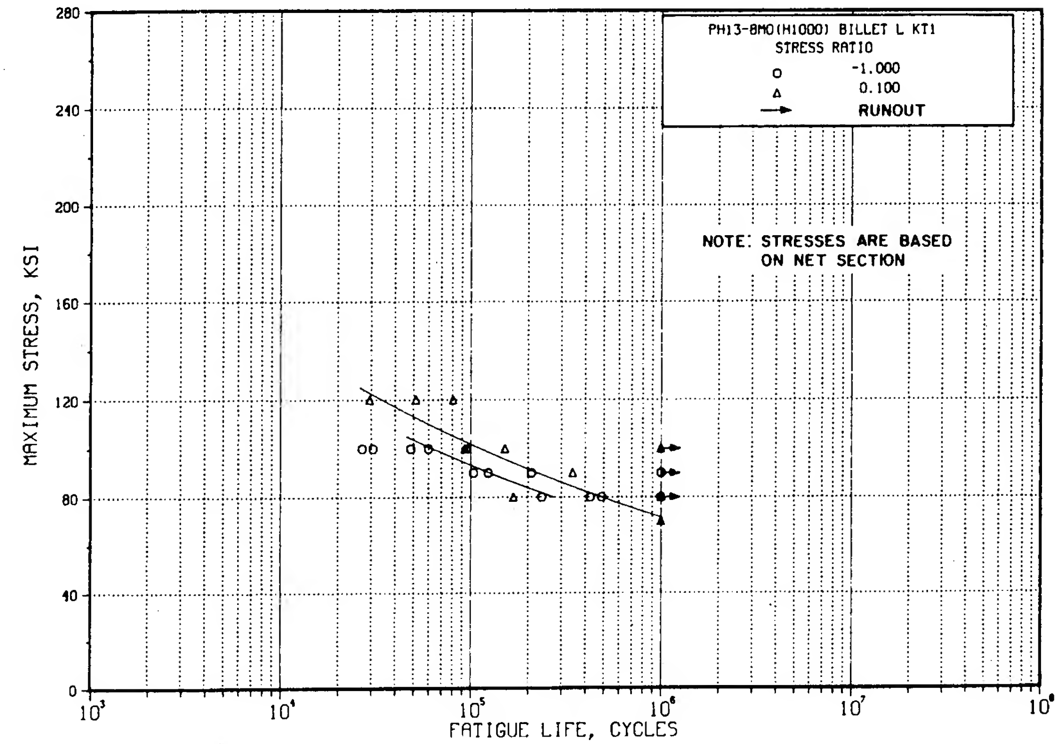

FIGURE 2.6.5.1.8(c). *Best-fit S/N curves for unnotched PH13-8Mo (H1000) hand forging, longitudinal direction.*

Correlative Information for Figure 2.6.5.1.8(c)

Product Form: Hand forging, 7 x 7 inches

Properties:	TUS, ksi	TYS, ksi	Temp., F
	210	204	RT

Specimen Details: Unnotched
0.500-inch gross diameter
0.250-inch net diameter

Surface Condition: Machined to RMS 63–270, solution treated and aged, grit blasted

Reference: 2.6.5.1.8(c)

Test Parameters:

Loading - Axial
Frequency - Not Specified
Temperature - RT
Environment - Air

No. of Heats/Lots: 2

Equivalent Stress Equation:

Log N_f = 18.12–6.54 log (S_{eq})
$S_{eq} = S_{max} (1-R)^{0.11}$
Standard Error of Estimate = 0.263
Standard Deviation in Life = 0.475
R^2 = 69%

Sample Size = 20

[Caution: The equivalent stress model may provide unrealistic life predictions for stress ratios beyond those represented above]

2.6.6 15-5PH

2.6.6.0 *Comments and Properties.*—15-5PH is a precipitation-hardening, martensitic stainless steel used for parts requiring corrosion resistance and high strength at temperatures up to 600 F. Alloy 15-5PH has good transverse ductility and strength in large section sizes. This material is supplied in either the annealed or overaged condition and is heat treated after fabrication. Parts should never be used in Condition A. When good fracture toughness or impact properties are required, both at or below room temperature, conditions H900 and H925 should not be used. Conditions H1025, H1075, H1100, and H1150 provide lower transition temperatures and more useful levels of fracture toughness than the H900 and H925 conditions. The H1150M condition has the best notch toughness and is recommended for cryogenic applications.

Manufacturing Considerations.—15-5PH is readily forged and welded. Forging procedures are similar to those used for 17-4PH, the forgeability of 15-5PH being superior to that of 17-4PH in critical types of upset-forging and hot-flattening operations. Machining in the solution-treated condition is done at rates similar to Type 304 and 60 percent of these rates work well for Condition H900. Highest machining rates are possible with Conditions H1150 and H1150M. Material which is hot worked must be solution-treated before hardening. A dimensional contraction of 0.0004 to 0.0006 and 0.0008 to 0.0010 in./in. will occur on hardening to the H900 and H1150 conditions, respectively.

Heat Treatment.—15-5PH must be used in the heat-treated condition and should not be placed in service in Condition A. The alloy can be heat treated to various strength levels having a wide range of properties. Consult the applicable material specification or MIL-H-6875 for specific heat treatment procedures.

Environmental Considerations.—The corrosion resistance of 15-5PH is comparable to that of 17-4PH. For tensile applications where stress corrosion is a possibility, 15-5PH should be aged at the highest temperature compatible with strength requirements and at a temperature not lower than 1025 F for 4 hours minimum aging time.

Specifications and Properties.—Material specifications for 15-5PH are presented in Table 2.6.6.0(a). Room-temperature mechanical and physical properties of 15-5PH are shown in Tables 2.6.6.0(b) through (d). The effect of temperature on physical properties is depicted in Figure 2.6.6.0.

TABLE 2.6.6.0(a). *Material Specifications for 15-5PH Stainless Steel*

Specification	Form
AMS 5659	Bar, forging, ring, and extrusion (CEVM)
AMS 5862	Sheet, strip, and plate (CEVM)
AMS 5400	Investment casting

2.6.6.1 *Various Heat-Treated Conditions.*—Elevated temperature curves for the various mechanical properties are shown in Figures 2.6.6.1.1 and 2.6.6.1.4. Typical stress-strain and tangent-modulus curves are shown in Figures 2.6.6.1.6(a) through (c).

2.6.6.2 *H1025 Condition.*—An elevated temperature curve for compressive yield strength is presented in Figure 2.6.6.2.2. Stress-strain and tangent-modulus curves are shown in Figures 2.6.6.2.6(a) and (b). Fatigue data at room temperature are illustrated in Figures 2.6.6.2.8(a) through (c).

2.6.6.3 *H1150 Condition.*—An elevated temperature curve for compressive yield strength is presented in Figure 2.6.6.3.2. Compressive stress-strain and tangent-modulus curves at various temperatures are shown in Figure 2.6.6.3.6.

TABLE 2.6.6.0(b). *Design Mechanical and Physical Properties of 15-5PH Stainless Steel Bar and Forging*

Specification	AMS 5659						
Form	Bar and forging						
Condition	H900	H925	H1025	H1075	H1100	H1150	H1150M[a]
Thickness or diam., in.	≤12	≤12	≤12	≤12	≤12	≤12	≤12
Basis	S	S	S	S	S	S	S
Mechanical Properties:							
F_{tu}, ksi:							
L	190	170	155	145	140	135	115
T	190	170	155	145	140	135	115
F_{ty}, ksi:							
L	170	155	145	125	115	105	75
T	170	155	145	125	115	105	75
F_{cy}, ksi:							
L	...	...	143	...	...	99	...
T	...	...	143	...	...	99	...
F_{su}, ksi	...	...	97	...	...	85	...
F_{bru}[b], ksi:							
(e/D = 1.5)	...	...	263	...	...	230	...
(e/D = 2.0)	...	...	332	...	...	293	...
F_{bry}[b], ksi:							
(e/D = 1.5)	...	...	211	...	...	166	...
(e/D = 2.0)	...	...	250	...	...	201	...
e, percent:							
L	10	10	12	13	14	16	18
T	6	7	8	9	10	11	14
RA, percent:							
L	35	38	45	45	45	50	55
T	20	25	32	33	34	35	35
E, 10^3 ksi	28.5						
E_c, 10^3 ksi	29.2						
G, 10^3 ksi	11.2						
μ	0.27						
Physical Properties:							
ω, lb/in.^{3}	0.283						
C, Btu/(lb)(F)	...						
K and α	See Figure 2.6.6.0						

[a]H1150M condition is not covered by AMS 5659; properties reflect producers' guaranteed minimum tensile properties.
[b]Bearing values are "dry pin" values per Section 1.4.7.1.

TABLE 2.6.6.0(c). *Design Mechanical and Physical Properties of 15-5PH Stainless Steel Plate*

Specification	AMS 5862			
Form	Plate			
Condition	H1025[a]			
Thickness, in.	0.187-0.625	0.626-2.000	2.001-3.000	3.001-4.000
Basis	S	S	S	S
Mechanical Properties:				
F_{tu}, ksi:				
L	154	154	154	...
LT	155	155	155	155
F_{ty}, ksi:				
L	143	143	143	...
LT	145	145	145	145
F_{cy}, ksi:				
L	150	150	150	...
LT	152	149	146	...
F_{su}, ksi	97	97	96	...
F_{bru}[b], ksi:				
(e/D = 1.5)	257	257	257	...
(e/D = 2.0)	331	331	331	...
F_{bry}[b], ksi:				
(e/D = 1.5)	211	211	211	...
(e/D = 2.0)	246	246	246	...
e, percent:				
LT	8	12	12	12
RA, percent:				
LT	35	40	40	40
E, 10^3 ksi	28.5			
E_c, 10^3 ksi	29.2			
G, 10^3 ksi	11.2			
μ	0.27			
Physical Properties:				
ω, lb/in.^{3}	0.283			
C, Btu/(lb)(F)	...			
K and α	See Figure 2.6.6.0			

[a]The H900, H925, H0175, H1100, and H1150 conditions are included in AMS 5862.
[b]Bearing values are "dry pin" values per Section 1.4.7.1.

TABLE 2.6.6.0(d). *Design Mechanical and Physical Properties of 15-5PH Stainless Steel Investment Casting*

Specification	AMS 5400
Form	Investment casting
Condition	H935
Location within casting	Any area
Basis	S
Mechanical Properties:[a]	
F_{tu}, ksi	170
F_{ty}, ksi	150
F_{cy}, ksi	155
F_{su}, ksi	107
$F_{bru}{}^{b}$, ksi:	
(e/D = 1.5)	269
(e/D = 2.0)	349
$F_{bry}{}^{b}$, ksi:	
(e/D = 1.5)	209
(e/D = 2.0)	240
e, percent	6
RA, percent	14
E, 10^3 ksi	28.5
E_c, 10^3 ksi	29.2
G, 10^3 ksi	11.2
μ	0.27
Physical Properties:	
ω, lb/in.^{3}	0.283
C, Btu/(lb)(F)	...
K, and α	See Figure 2.6.6.0

[a]Properties apply only when drawing specifies that conformance to tensile property requirements shall be determined from specimens cut from castings or integrally cast specimens.
[b]Bearing values are "dry pin" values per Section 1.4.7.1.

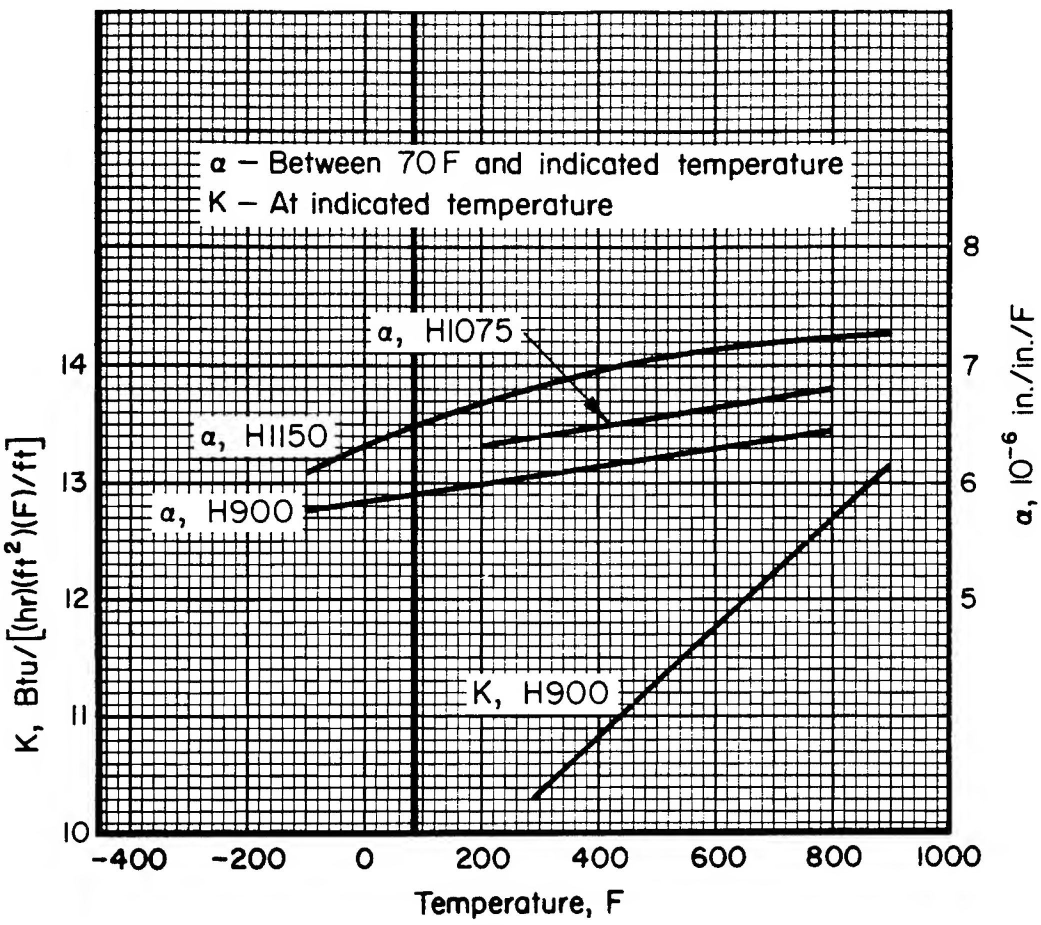

FIGURE 2.6.6.0. *Effect of temperature on the physical properties of 15-5PH stainless steel.*

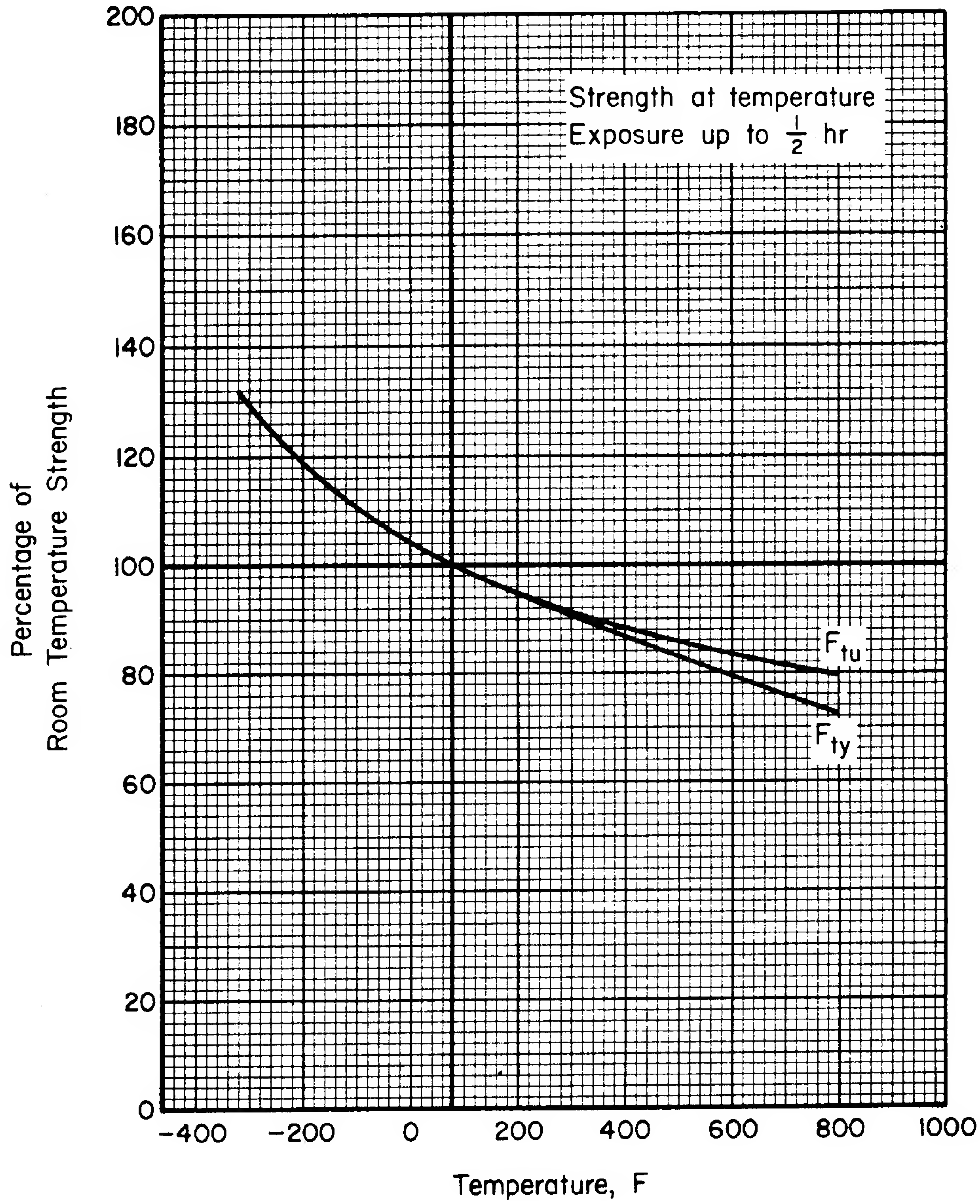

FIGURE 2.6.6.1.1. *Effect of temperature on the tensile ultimate strength (F_{tu}) and the tensile yield strength (F_{ty}) of 15-5PH (H925, H1025, and H1100) stainless steel bar.*

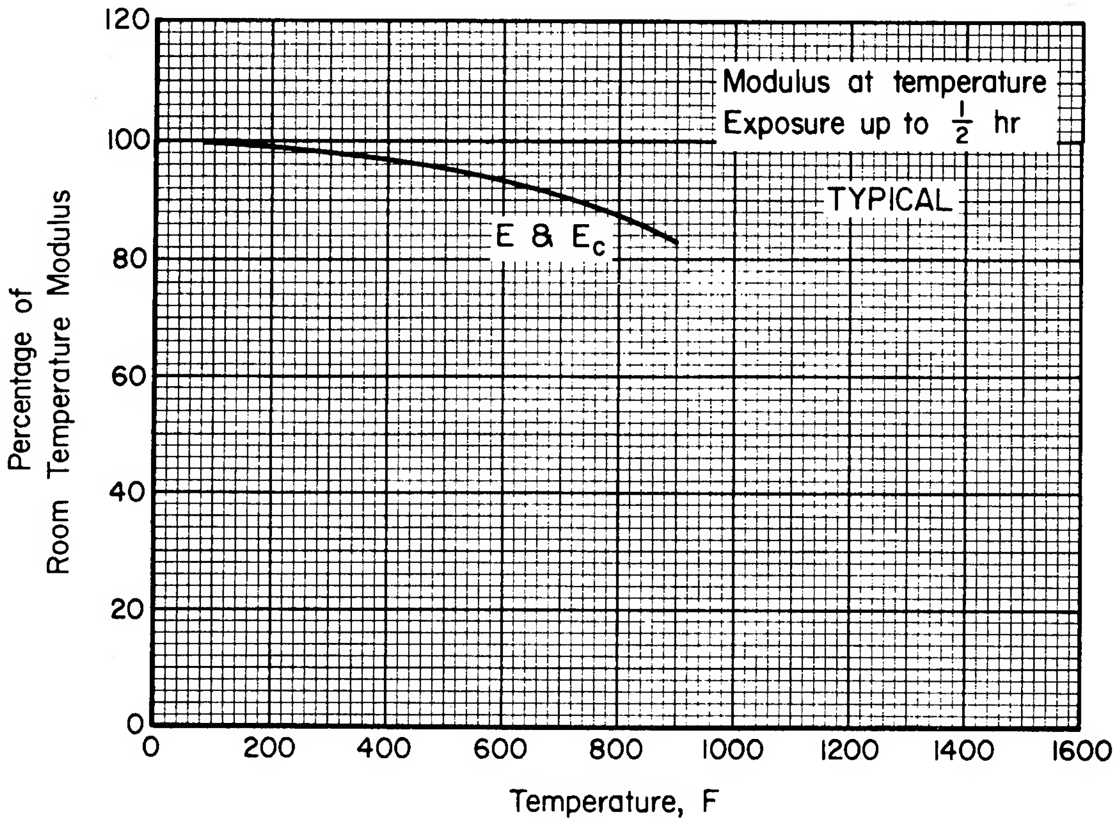

FIGURE 2.6.6.1.4. *Effect of temperature on the tensile and compressive moduli (E and E_c) of 15-5PH stainless steel.*

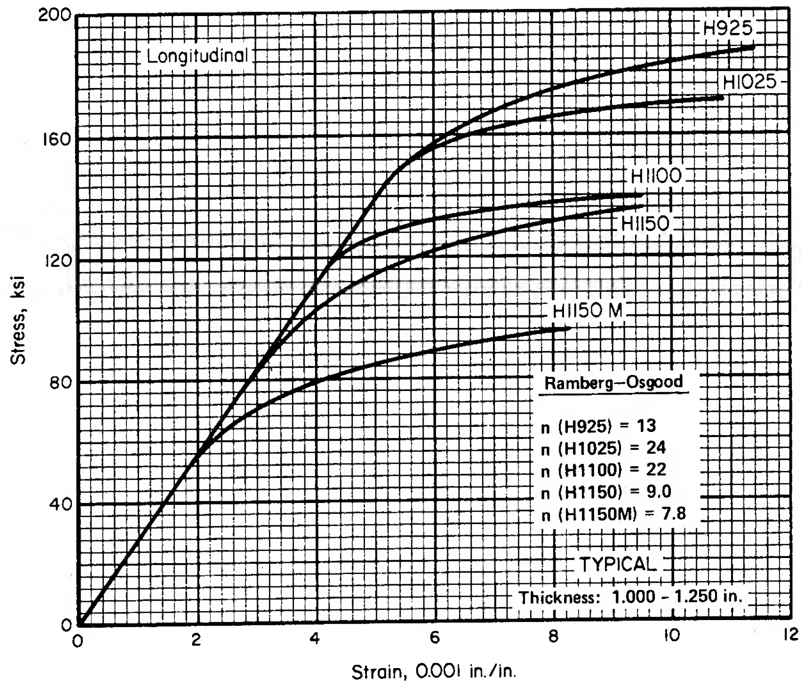

FIGURE 2.6.6.1.6(a). *Typical tensile stress-strain curves at room temperature for various heat treated conditions of 15-5PH stainless bar.*

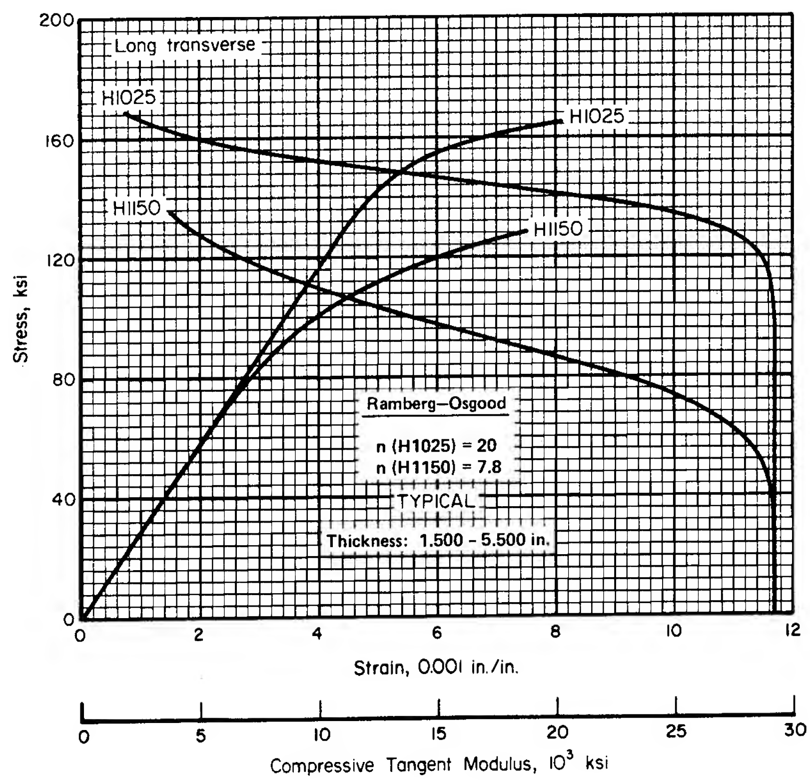

FIGURE 2.6.6.1.6(b). *Typical compressive stress-strain and compressive tangent-modulus curves at room temperature for various heat-treated conditions of 15-5PH stainless steel bar.*

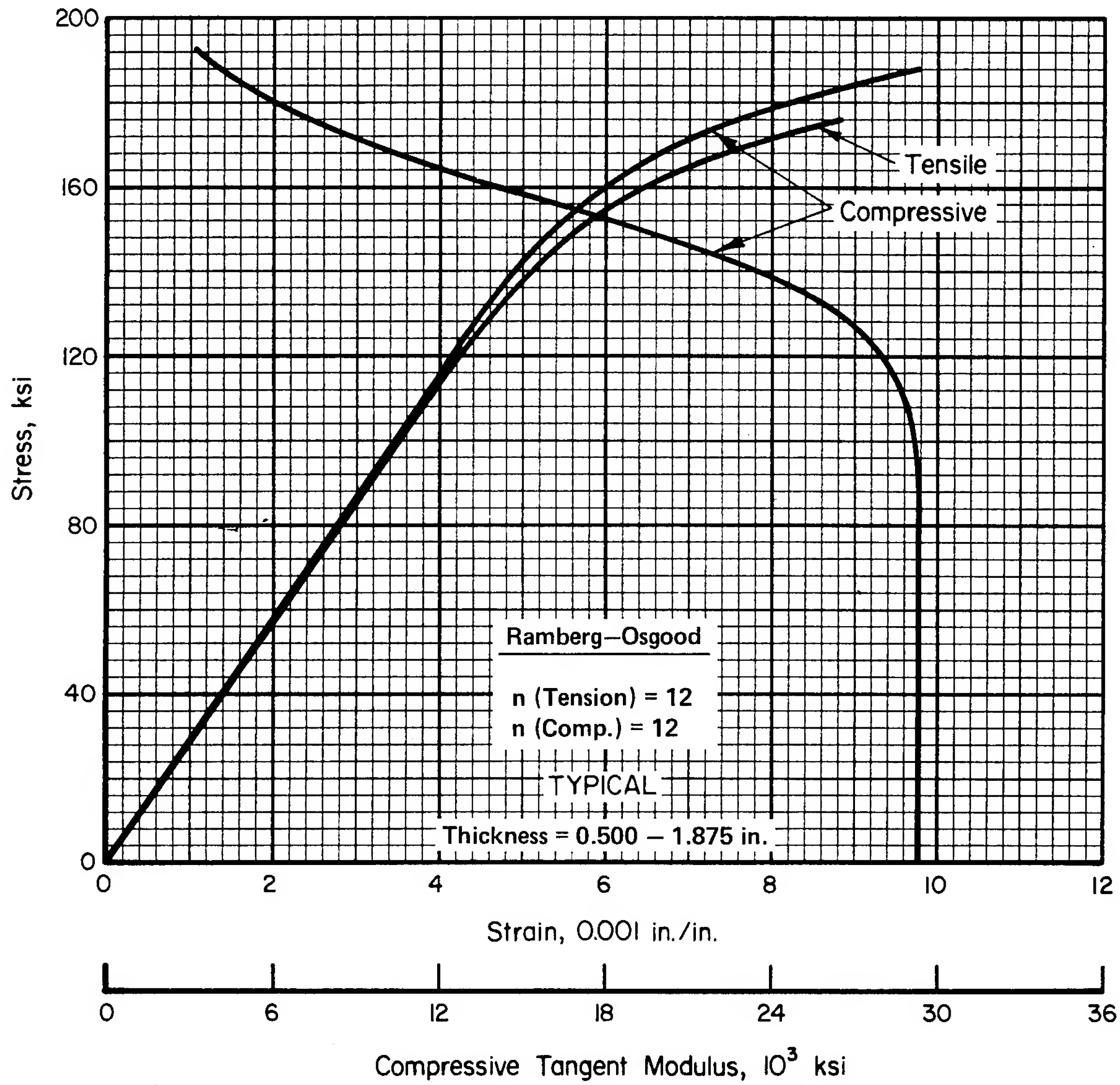

FIGURE 2.6.6.1.6(c). *Typical tensile and compressive stress-strain and compressive tangent-modulus curves for 15-5PH (H935) stainless steel casting.*

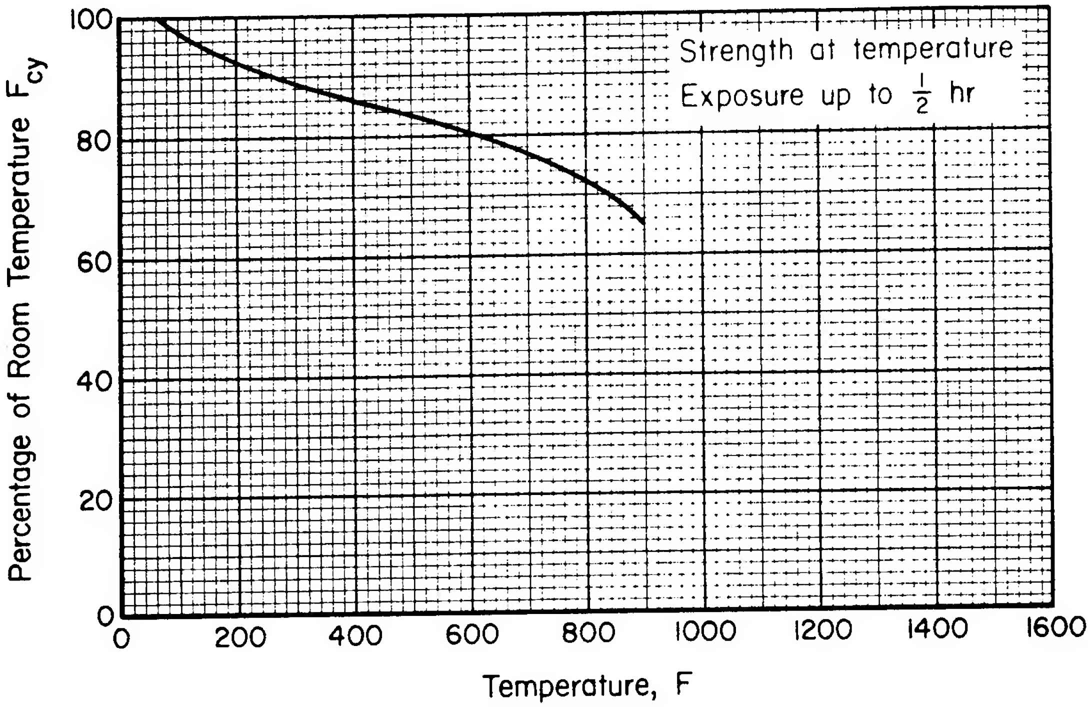

FIGURE 2.6.6.2.2. *Effect of temperature on the compressive yield strength (F_{cy}) of 15-5PH (H1025) stainless steel bar.*

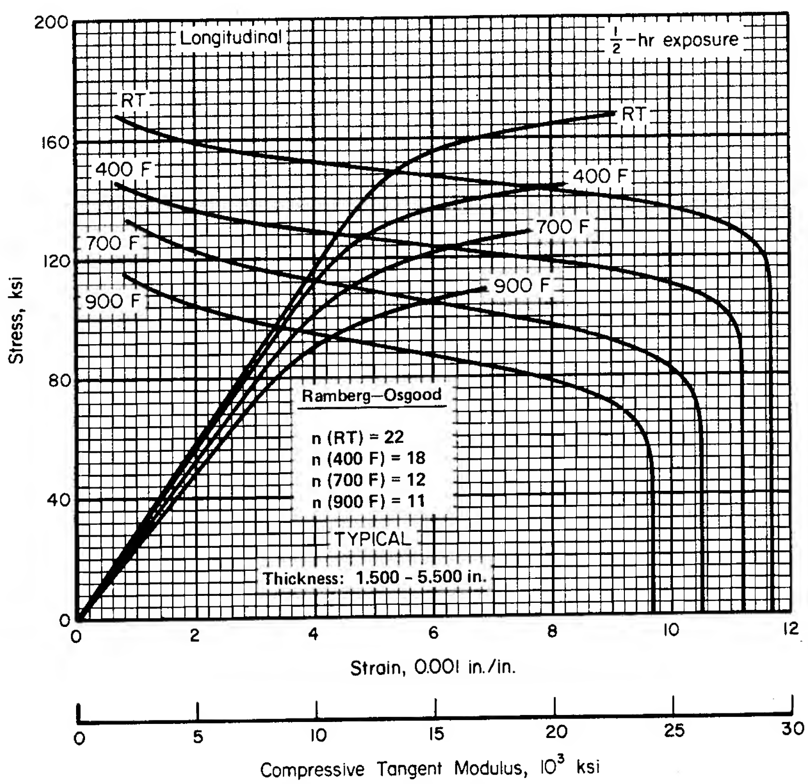

FIGURE 2.6.6.2.6(a). *Typical compressive stress-strain and compressive tangent-modulus curves at various temperatures for 15-5PH (H1025) stainless steel bar.*

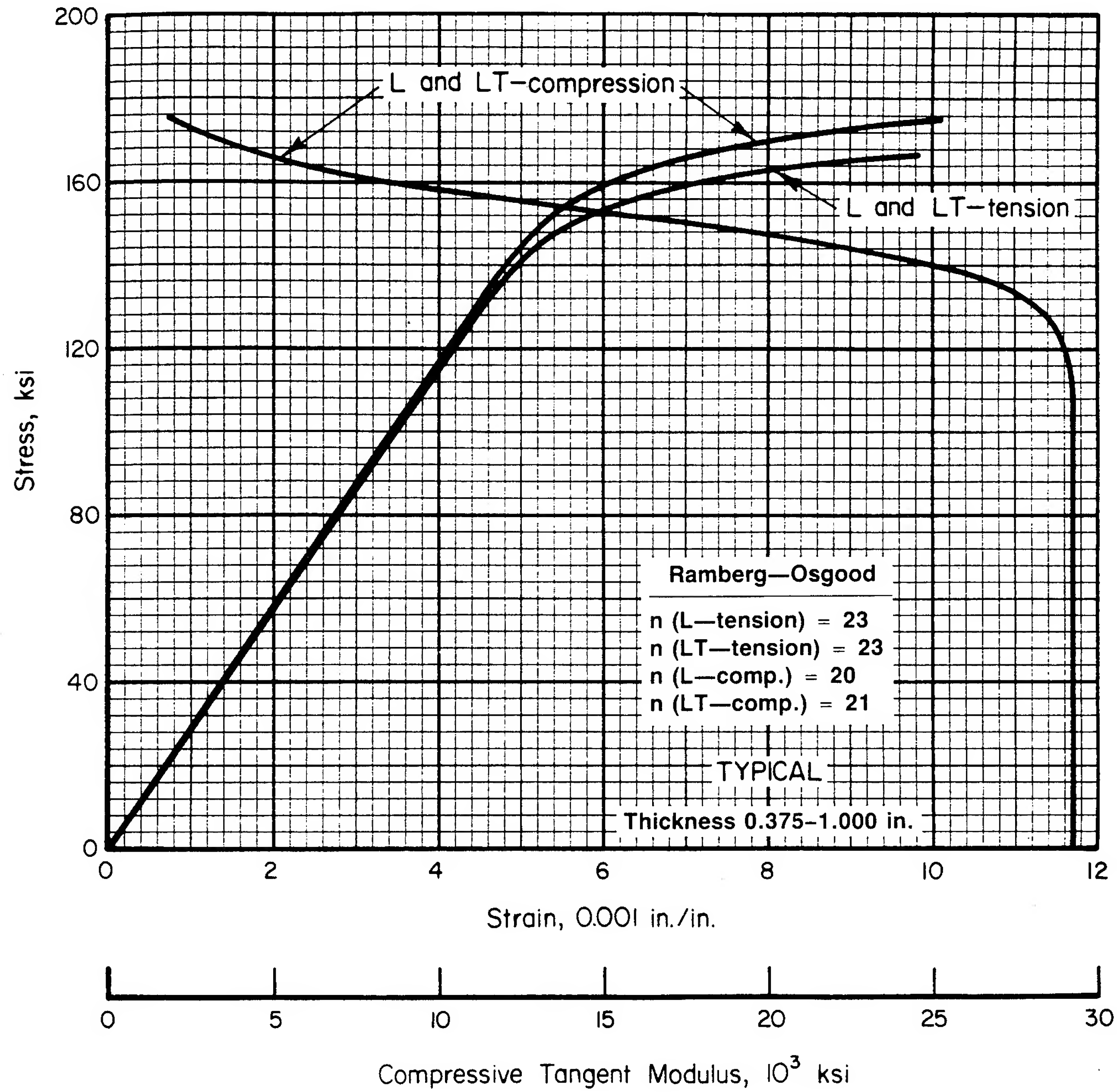

FIGURE 2.6.6.2.6(b). *Tensile and compressive stress-strain and compressive tangent-modulus curves for 15-5PH (H1025) stainless steel plate.*

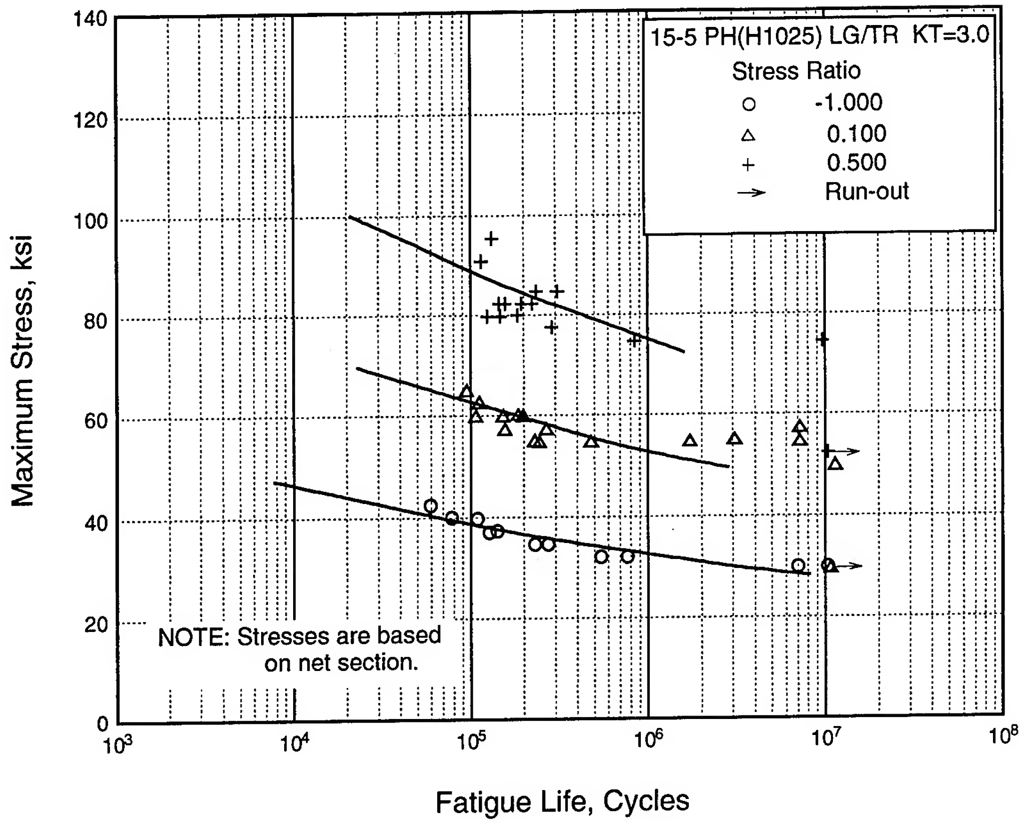

FIGURE 2.6.6.2.8(a). *Best-fit S/N curves for notched, K_t = 3.0, 15-5PH (H1025) stainless steel bar, longitudinal and long transverse directions.*

Correlative Information for Figure 2.6.6.2.8(a)

Product Form: Bar, 2 x 6 inches

Properties:	TUS, ksi	TYS, ksi	Temp, F
Longitudinal	163	159	RT
Long Transverse	164	160	RT
Longitudinal	278	--	RT (notched)
Long Transverse	277	--	RT (notched)

Specimen Details: Notched, V-Groove, K_t = 3.0
0.375-inch gross diameter
0.250-inch net diameter
0.013-inch root radius, *r*
60° flank angle, ω

Surface Condition: Ground notch

Reference: 2.6.6.2.8(a)

Test Parameters
Loading - Axial
Frequency - 1800 cpm
Temperature - RT
Environment - Air

No. of Heats/Lots: 3

Equivalent Stress Equation
$\text{Log } N_f = 19.69 - 9.14 \log (S_{eq} - 18.16)$
$S_{eq} = S_{max} (1 - R)^{0.595}$
Standard Error of Estimate = 0.449
Standard Deviation in Life = 0.627
R^2 = 49%

Sample Size: 40

[Caution: The equivalent stress model may provide unrealistic life predictions for stress ratios beyond those represented above.]

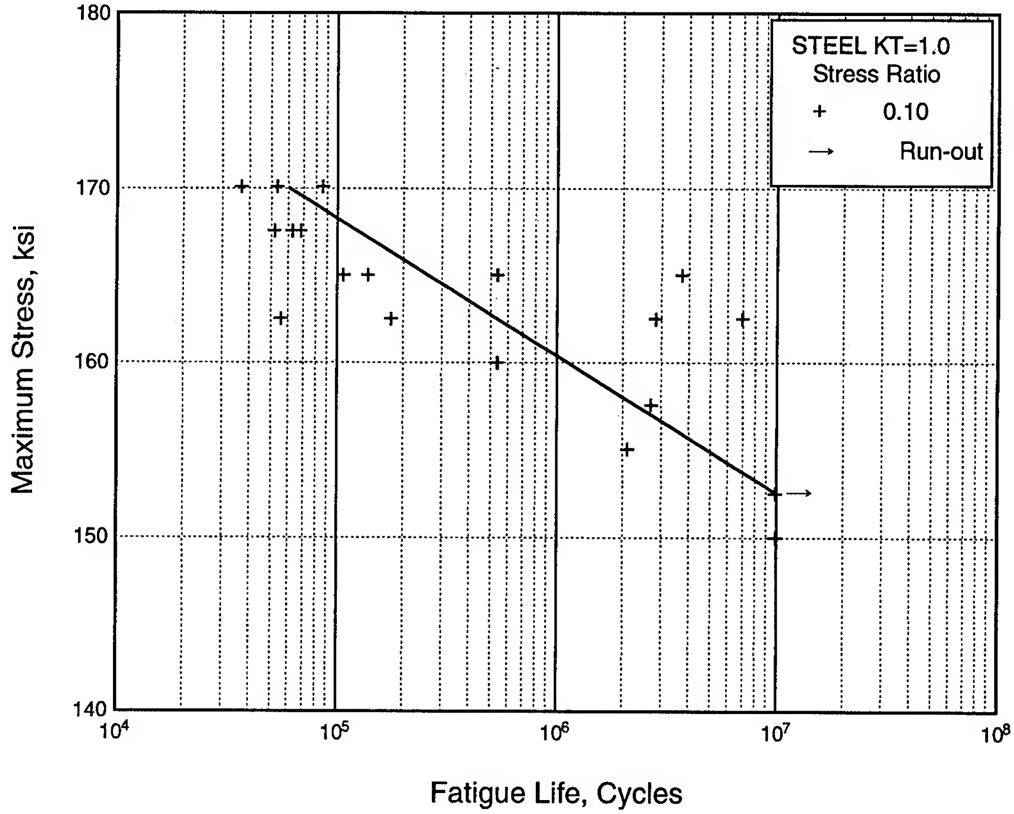

FIGURE 2.6.6.2.8(b). *Best-fit S/N curve for unnotched, K_t = 1.0, 15-5PH (H1025) stainless steel plate, longitudinal and long transverse directions.*

Correlative Information for Figure 2.6.6.2.8(b)

Product Form: Plate, 0.808 inch, 2.024 inch, and 2.579 inch thick

Properties:	TUS, ksi	TYS, ksi	Temp, F
Longitudinal	169.9	165.7	RT
Long Transverse	170.2	166.1	RT

Specimen Details: Unnotched
0.250-inch diameter

Surface Condition: Axial, ground RMS 8

Reference: 2.6.6.2.8(b)

Test Parameters:
Loading - Axial
Frequency - 30 Hz
Temperature - RT
Atmosphere - Air

No. of Heats/Lots: 4

Fatigue Life Equation:
$\text{Log } N_f = 110.1 - 47.22 \log (S_{max})$

Standard Deviation in Log (Life) = 0.58

Adjusted R^2 = 52.8%

Sample Size = 19

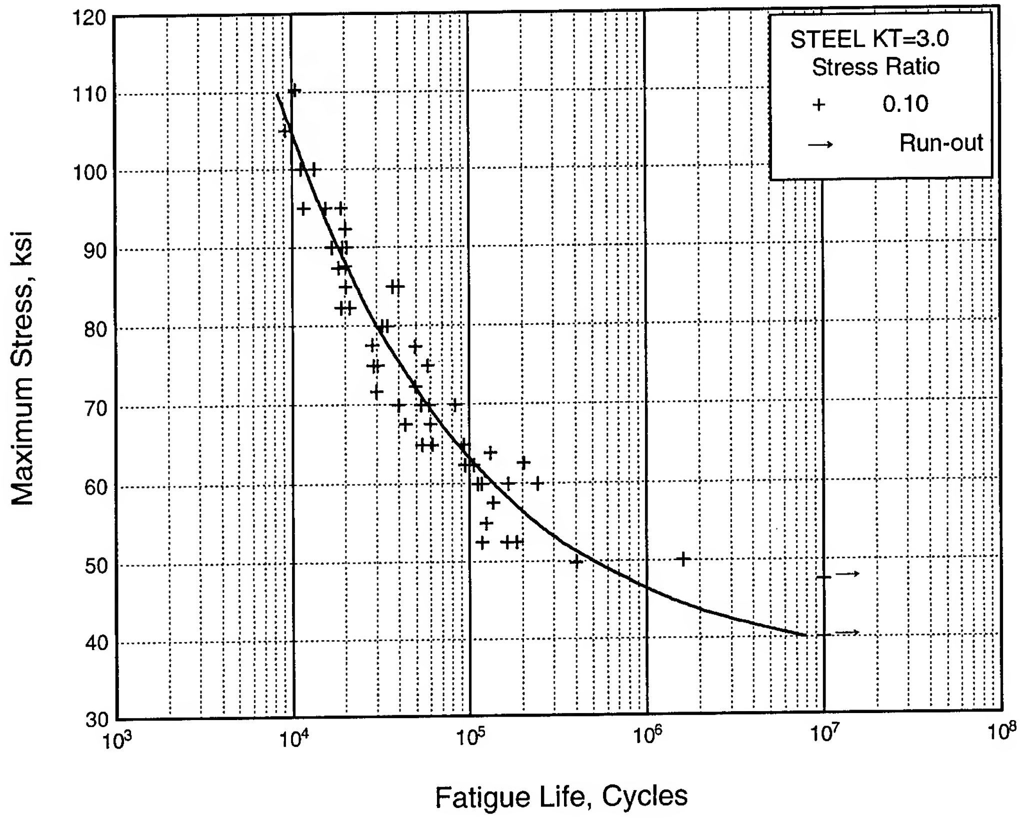

FIGURE 2.6.6.2.8(c). *Best-fit S/N curve for notched, K_t = 3.0, 15-5PH (H1025) stainless steel plate, longitudinal and long transverse directions.*

Correlative Information for Figure 2.6.6.2.8(c)

Product Form: Plate, 0.215 inch, 0.269 inch, 0.277 inch, 0.394 inch, 0.524 inch, 0.908 inch, 2.024 inch, and 2.579 inch

Properties:	TUS, ksi	TYS, ksi	Temp,F
Longitudinal	170.8	165.6	RT
Long Transverse	170.2	166.1	RT

Specimen Details: Notched V-Groove, K_t = 3.0
- Flat, 0.590-inch gross width
  - 0.500-inch net width
  - 0.025-inch root radius
  - 60° flank angle, ω
- Round, 0.374-inch gross diameter
  - 0.252-inch net diameter
  - 0.013-inch root radius
  - 60° flank angle, ω

Surface Condition: RMS 32 notch

Reference: 2.6.6.2.8(b)

Test Parameters:
- Loading - Axial
- Frequency - 30 Hz
- Temperature - RT
- Atmosphere - Air

No. of Heats/Lots: 10

Fatigue Life Equation:
$\log N_f = 8.72 - 2.56 \log (S_{max} - 34.9)$

Standard Deviation in Log (Life) = 10.9 ($1/S_{max}$)

Adjusted R^2 = 88.2%

Sample Size = 55

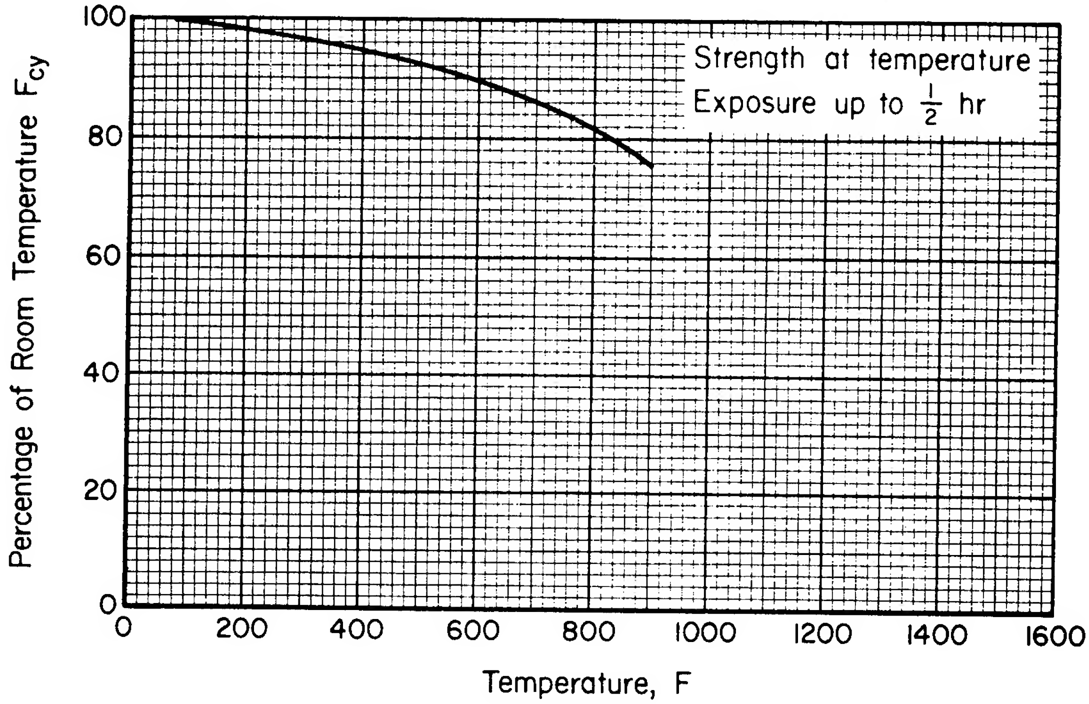

FIGURE 2.6.6.3.2. *Effect of temperature on the compressive yield strength (F_{cy}) of 15-5PH (H1150) stainless steel bar.*

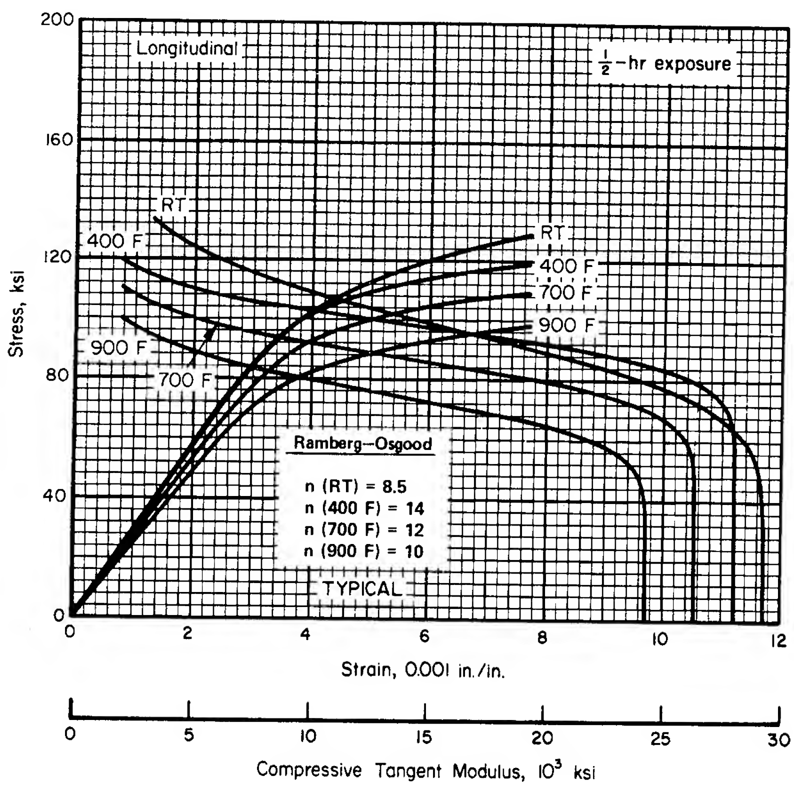

FIGURE 2.6.6.3.6. *Typical compressive stress-strain and tangent-modulus curves at various temperatures for 15-5PH (H1150) stainless steel bar.*

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2.6.7 PH15-7Mo

2.6.7.0 *Comments and Properties.*—PH15-7Mo is a semiaustenitic stainless steel used where high strength and good corrosion and oxidation resistance are needed up to 600 F. This steel is supplied in Condition A of ease for forming or in Condition C when highest strength is required.

Manufacturing Considerations.—PH15-7Mo in Condition A is readily cold formed. Conventional inert-gas shielded arc and resistance techniques are generally used for welding. The heat treatments for this steel are compatible with the cycles used for honeycomb panel brazing. Vapor blasting of scaled Condition TH1050 parts is recommended because of the hazards of intergranular corrosion in adequately controlled pickling operations.

In hardening this steel from Condition A to Condition TH1050 a net dimensional growth of 0.004 in./in. should be anticipated. Use of this steel in Conditions T and T-100 is not recommended.

Environmental Considerations—The resistance of PH15-7Mo to stress-corrosion cracking in chloride environments has been evaluated and found to be superior to that of the alloy steels and the hardenable chromium steels. Conditions C and CH 900 provide maximum resistance to stress corrosion.

Specification and Properties.—A material specification for PH15-7Mo stainless steel is presented in Table 2.6.7.0(a). The room-temperature properties of PH15-7Mo are shown in Tables 2.6.7.0(b) and (c). The physical properties of this alloy at room and elevated temperatures are presented in Figure 2.6.7.0.

TABLE 2.6.7.0(a). *Material Specification for PH15-7Mo Stainless Steel*

Specification	Form
AMS 5520	Plate, sheet, and strip

2.6.7.1 *TH1050 Condition.*—Effect of temperature on various mechanical properties for this condition is presented in Figures 2.6.7.1.1 and 2.6.7.1.4. Typical stress-strain and tangent-modulus curves at room temperature and elevated temperature are presented in Figures 2.6.7.1.6(a) through (c). Unnotched and notched fatigue information at room and elevated temperatures are illustrated in Figures 2.6.7.1.8(a) through (f).

TABLE 2.6.7.0(b). *Design Mechanical and Physical Properties of PH15-7Mo Stainless Steel Sheet, Strip, and Plate*

Specification	AMS 5520
Form	Sheet, strip, and plate
Condition	TH1050
Thickness, in.	0.0015-0.500
Basis	S
Mechanical Properties:	
F_{tu}, ksi:	
L	185
LT	190
F_{ty}, ksi:	
L	165
LT	170
F_{cy}, ksi:	
L	182
LT	188
F_{su}, ksi	120
F_{bru}, ksi:	
(e/D = 1.5)	327
(e/D = 2.0)	377
F_{bry}, ksi:	
(e/D = 1.5)	259
(e/D = 2.0)	272
e, percent:	
LT	[a]
E, 10^3 ksi	29.0
E_c, 10^3 ksi	30.0
G, 10^3 ksi	11.4
μ	0.28
Physical Properties:	
ω, lb/in.^{3}	0.277
C, Btu(lb)(F)	...
K and α	See Figure 2.6.7.0

[a]See Table 2.6.7.0(c).

TABLE 2.6.7.0(c). *Minimum Elongation Values for PH15-7Mo (TH1050) Stainless Steel Sheet*

Thickness, inches	e (LT), percent
0.0015 to 0.0049	2
0.0050 to 0.0099	3
0.010 to 0.019	4
0.020 to 0.1874	5
0.1875 to 0.500	6

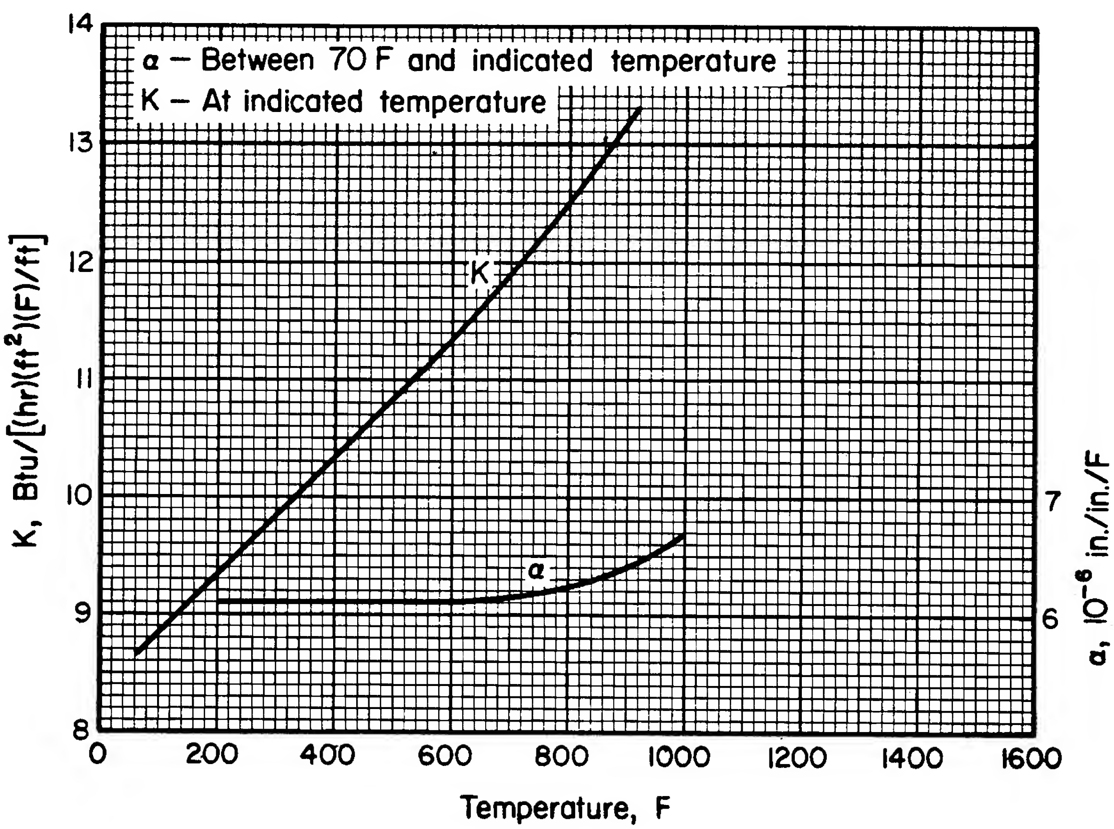

FIGURE 2.6.7.0. *Effect of temperature on the physical properties of PH15-7Mo (TH1050) stainless steel.*

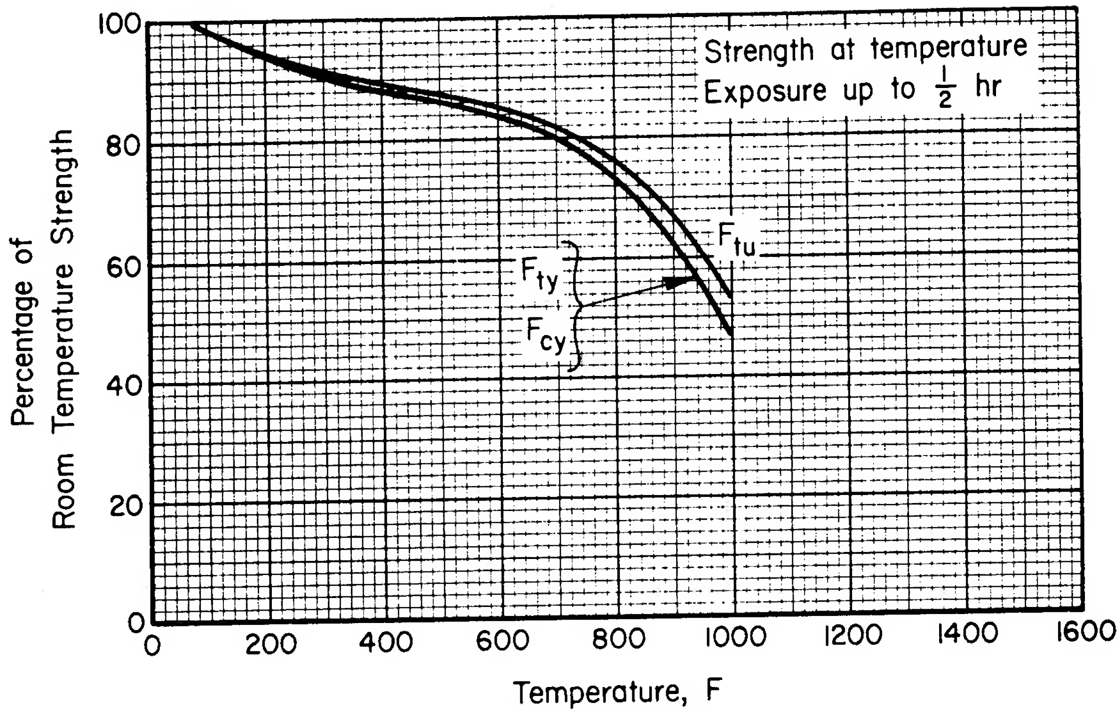

FIGURE 2.6.7.1.1. *Effect of temperature on the tensile ultimate strength (F_{tu}), tensile yield strength (F_{ty}), and compressive yield strength (F_{cy}) of PH15-7Mo (TH1050) stainless steel sheet.*

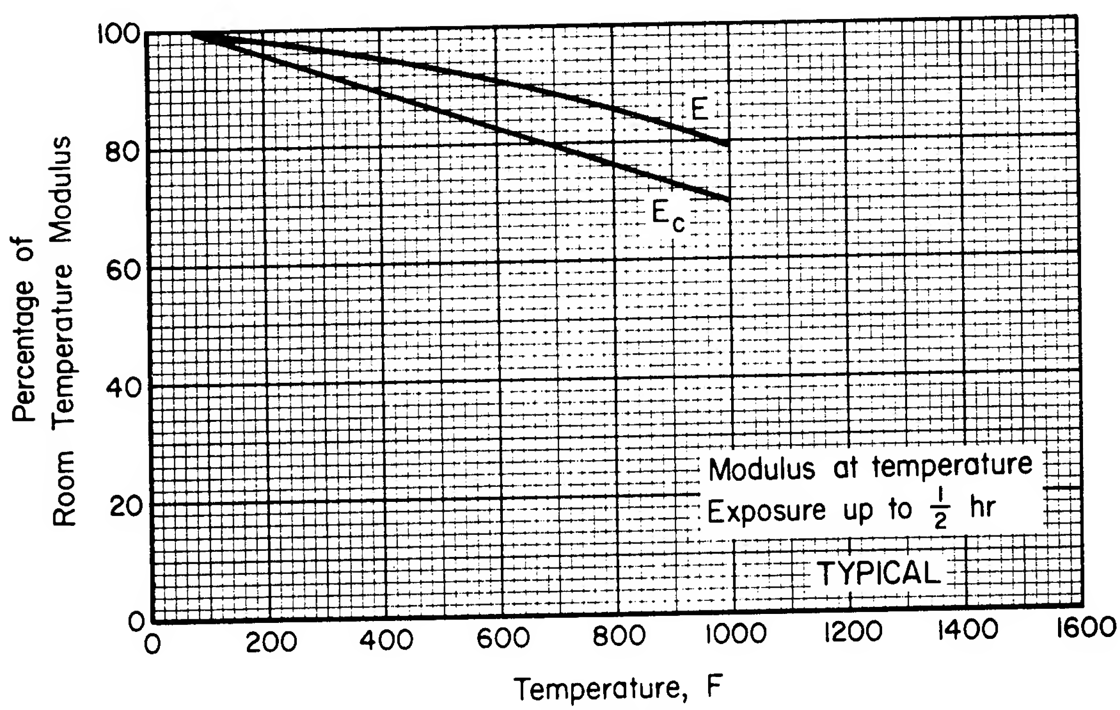

FIGURE 2.6.7.1.4. *Effect of temperature on the tensile and compressive moduli (E and E_c) of PH15-7Mo (TH1050) stainless steel sheet.*

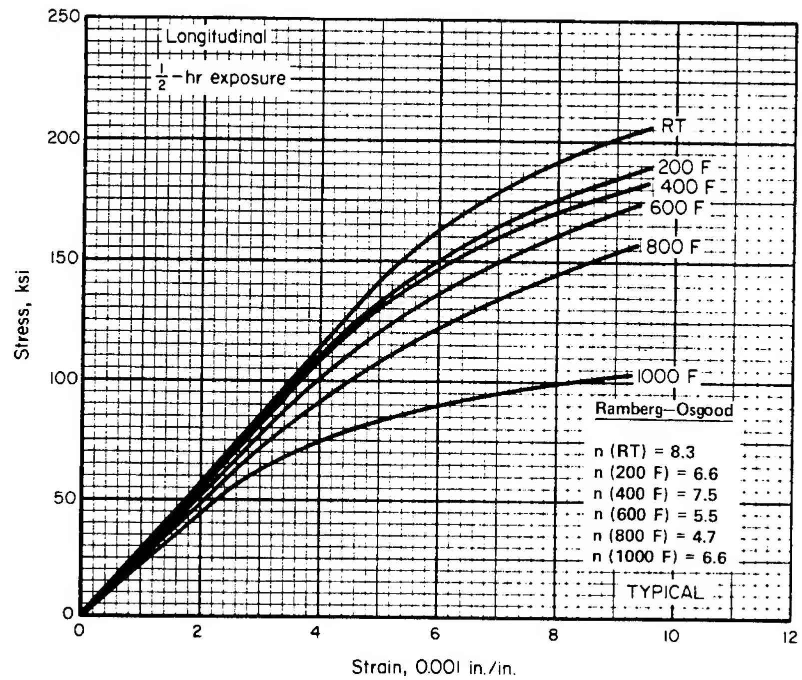

FIGURE 2.6.7.1.6(a). *Typical tensile stress-strain curves at various temperatures for PH15-7Mo (TH1050) stainless steel sheet.*

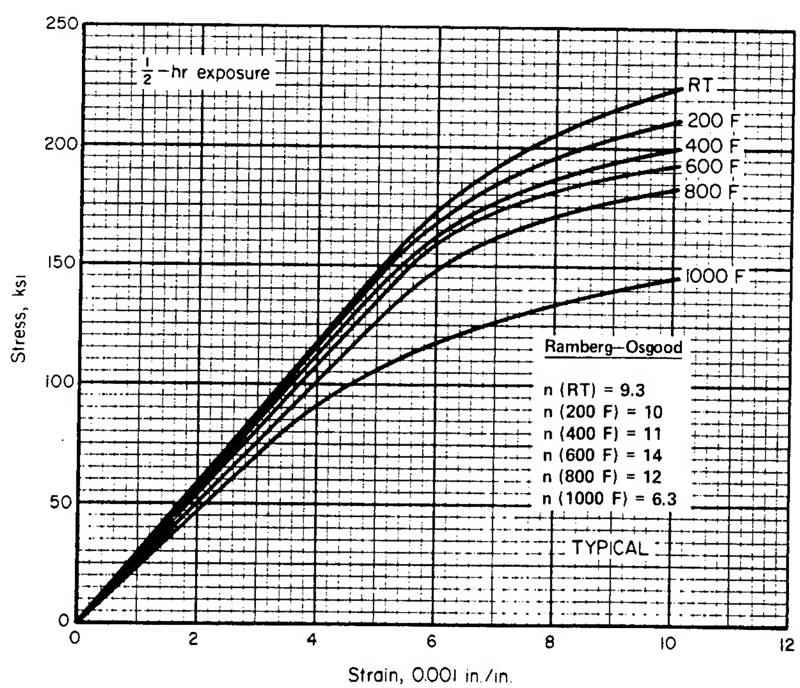

FIGURE 2.6.7.1.6.(b). *Typical compressive stress-strain curves at various temperatures for PH15-7Mo (TH1050) stainless steel sheet.*

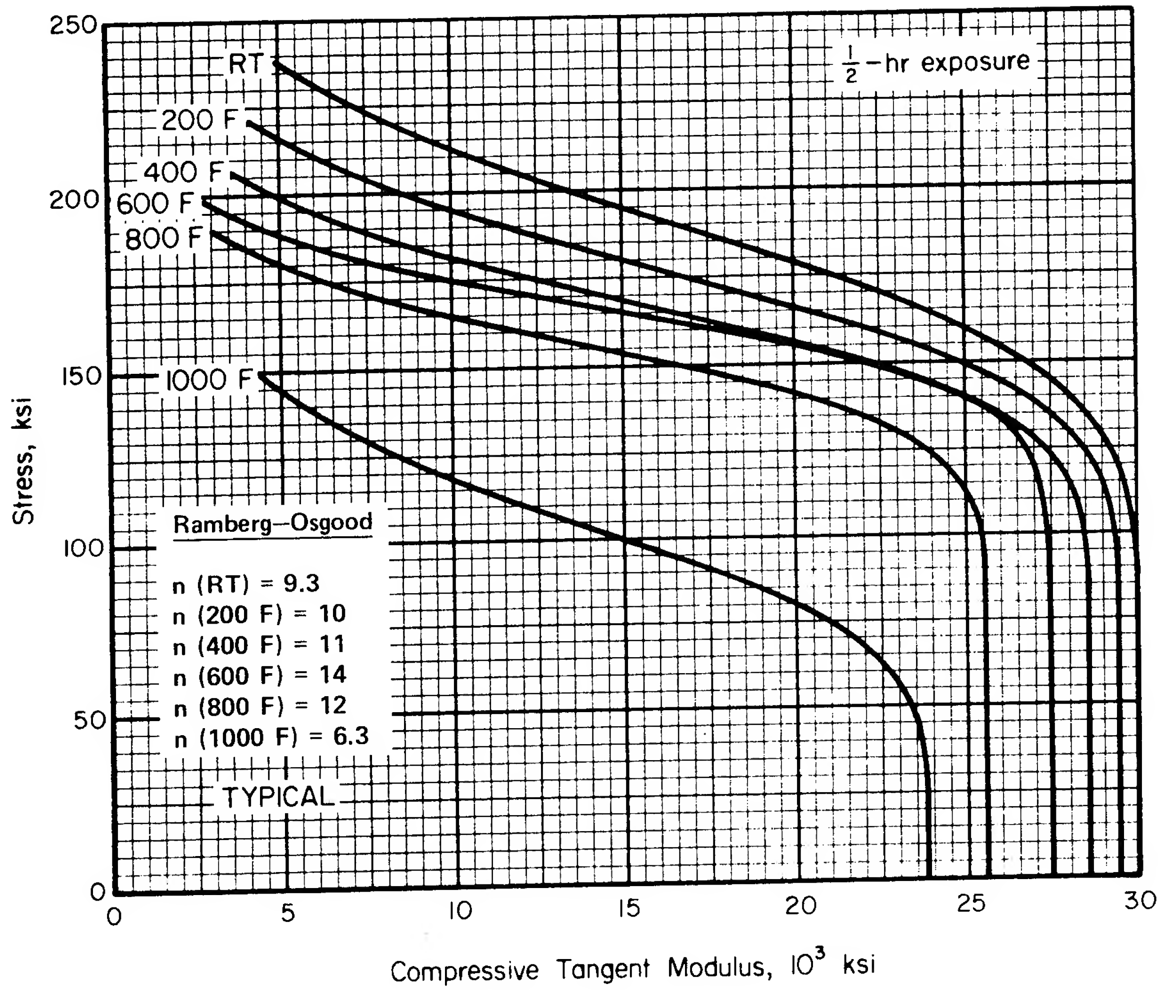

FIGURE 2.6.7.1.6(c). *Typical compressive tangent-modulus curves at various temperatures for PH15-7Mo (TH1050) stainless steel sheet.*

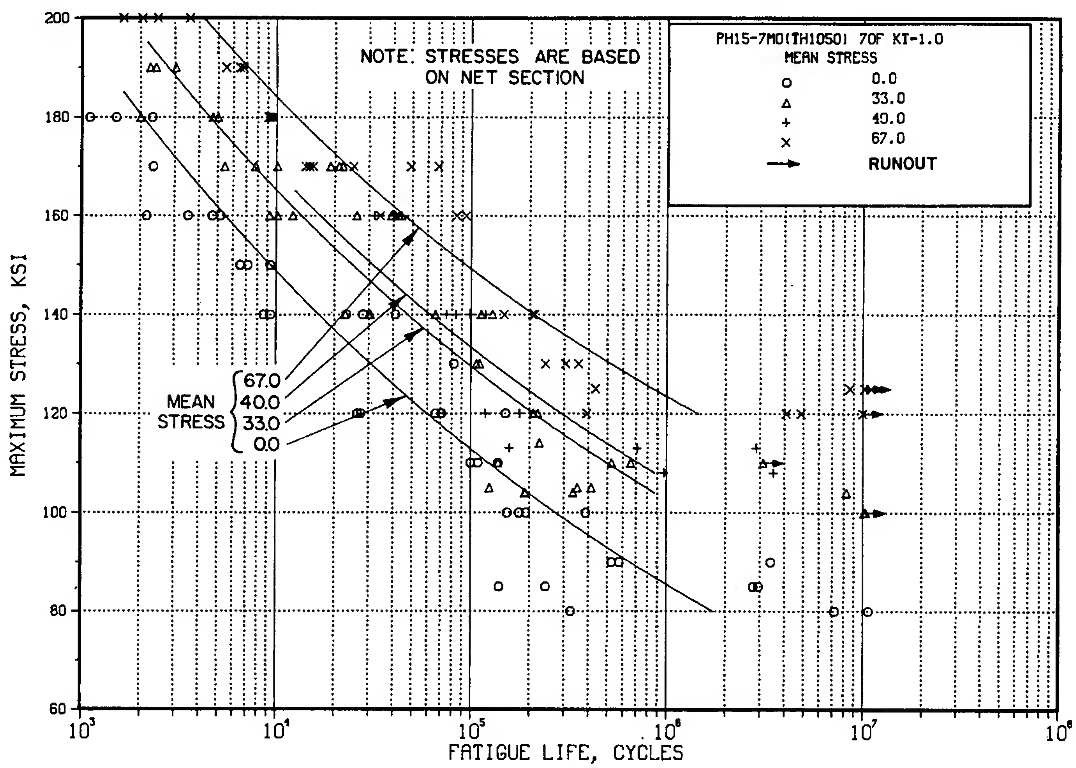

FIGURE 2.6.7.1.8(a). *Best-fit S/N curves for unnotched PH15-7Mo (TH1050) sheet, longitudinal direction.*

Correlative Information for Figure 2.6.7.1.8(a)

Product Form: Sheet, 0.025-inch

Properties:

TUS, ksi	TYS, ksi	Temp., F
201	196	RT

Specimen Details: Unnotched
2.0-inch gross width
0.75-inch net width

Surface Condition: Specimen edges machined in longitudinal direction, edges polished with 320 grit emery paper

References: 2.6.7.1.8(a) and (b)

Test Parameters:

Loading – Axial
Frequency – 24 and 1800 cpm
Temperature – RT
Environment – Air

No. of Heats/Lots: Not specified

Equivalent Stress Equation:

Log N_f = 23.24–8.32 log (S_{eq})
$S_{eq} = S_{max}\ (1\text{-}R)^{0.47}$
Standard Error of Estimate = 0.35
Standard Deviation in Life = 0.94
R^2 = 86%

Sample Size = 124

[Caution: The equivalent stress model may provide unrealistic life predictions for stress ratios beyond those represented above]

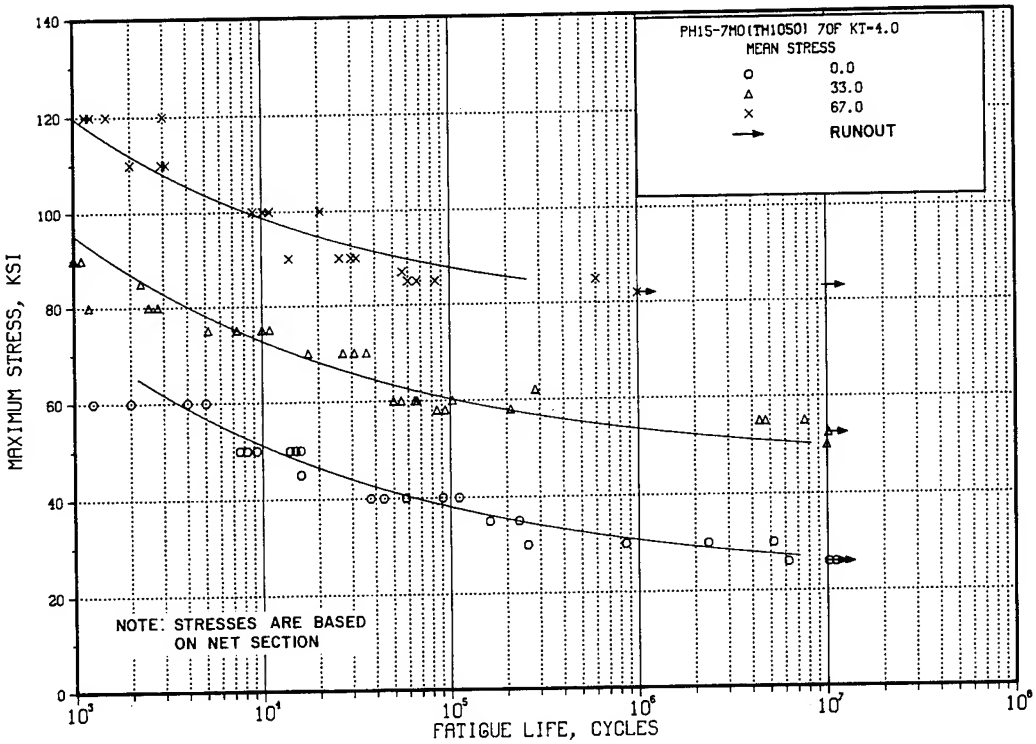

FIGURE 2.6.7.1.8(b). *Best-fit S/N curves for notched, K_t = 4.0, PH15-7Mo (TH1050) sheet, longitudinal direction.*

Correlative Information for Figure 2.6.7.1.8(b)

Product Form: Sheet, 0.025 inch

Properties:	TUS, ksi	TYS, ksi	Temp., F
	201	196	RT

Specimen Details: Edge Notched, K_t = 4.0
2.25-inch gross width
1.50-inch net width
0.058-inch notch radius
0° flank angle, ω

Surface Condition: Drilled holes near edges and slots milled from edge, corners of notch were beveled with rubber abrasive

Reference: 2.6.7.1.8(b)

Test Parameters:

Loading - Axial
Frequency - 24 and 1800 cpm
Temperature - RT
Environment - Air

No. of Heats/Lots: Not specified

Equivalent Stress Equation:

Log N_f = 10.42-3.91 log (S_{eq}-32)
$S_{eq} = S_{max} (1-R)^{0.58}$
Standard Error of Estimate = 0.36
Standard Deviation in Life = 1.07
R^2 = 89%

Sample Size = 74

[Caution: The equivalent stress model may provide unrealistic life predictions for stress ratios beyond those represented above]

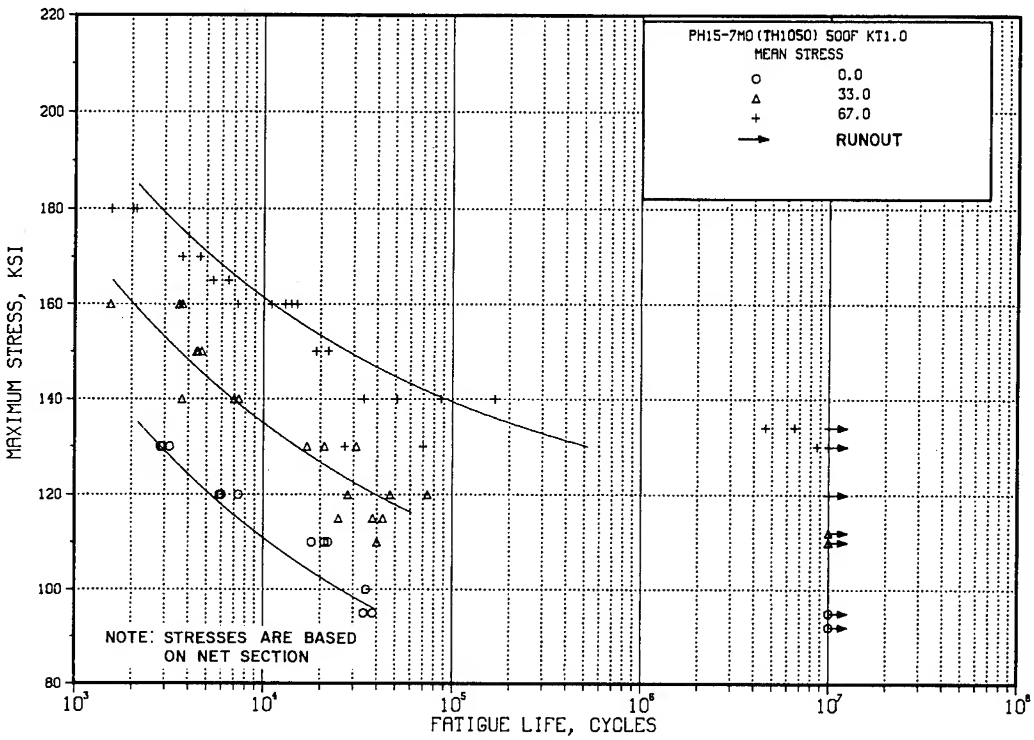

FIGURE 2.6.7.1.8(c). *Best-fit S/N curves for unnotched PH15-7Mo (H1050) sheet at 500 F, longitudinal direction.*

Correlative Information for Figure 2.6.7.1.8(c)

Product Form: Sheet, 0.025 inch

Properties:	TUS, ksi	TYS, ksi	Temp., F
	201	196	RT
	179	173	500

Specimen Details: Unnotched
2.00-inch gross width
0.75-inch net width

Surface Condition: Machined in longitudinal direction, edges polished with 320 grit emery paper

Reference: 2.6.7.1.8(b)

Test Parameters:

Loading - Axial
Frequency - 24 and 1800 cpm
Temperature - 500 F
Environment - Air

No. of Heats/Lots: Not specified

Equivalent Stress Equation:

Log N_f = 11.71-4.00 log (S_{eq}-96)
$S_{eq} = S_{max}\ (1\text{-}R)^{0.70}$
Standard Error of Estimate = 0.44
Standard Deviation in Life = 1.79
R^2 = 69%

Sample Size = 55

[Caution: The equivalent stress model may provide unrealistic life predictions for stress ratios beyond those represented above]

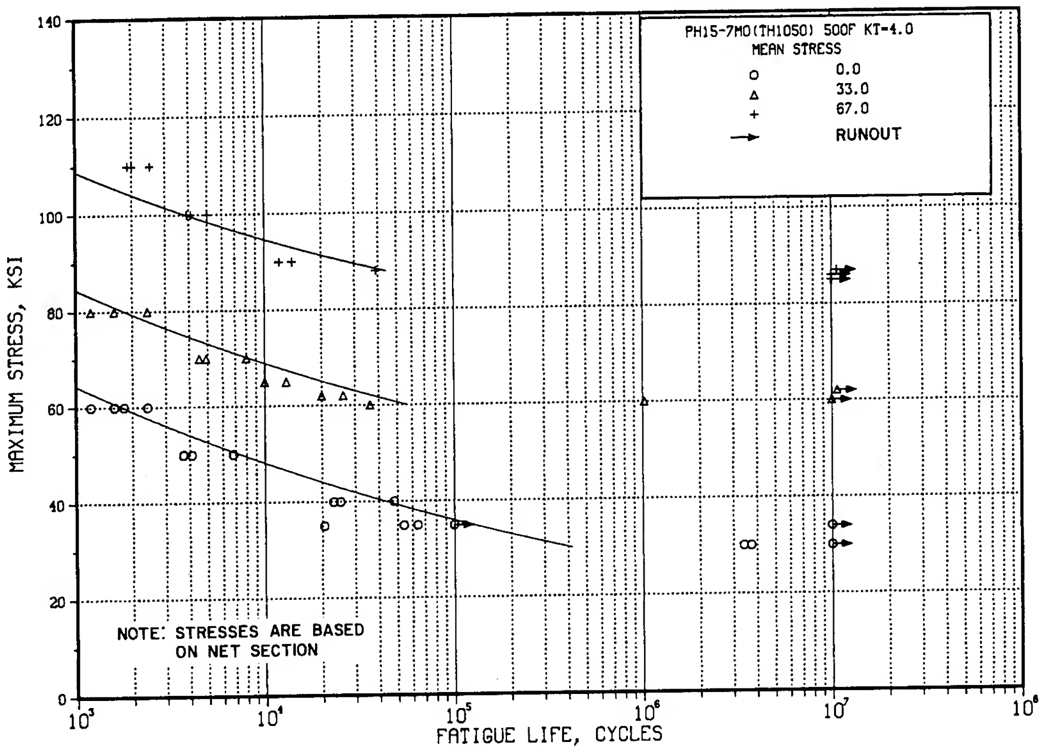

FIGURE 2.6.7.1.8(d). *Best-fit S/N curves for notched K_t = 4.0, PH15-7Mo (TH1050) sheet at 500 F, longitudinal direction.*

Correlative Information for Figure 2.6.7.1.8(d)

Product Form: Sheet, 0.025 inch

Properties:

TUS, ksi	TYS, ksi	Temp., F
201	196	RT
179	173	500

Specimen Details: Edge Notched, K_t = 4.0
2.25-inch gross width
1.50-inch net width
0.058-inch notch radius
0° flank angle, ω

Surface Condition: Drilled holes near edges and slots milled from edge, corners of notch were beveled with rubber abrasive

Reference: 2.6.7.1.8(b)

Test Parameters:

Loading - Axial
Frequency - 24 to 1800 cpm
Temperature - 500 F
Environment - Air

No. of Heats/Lots: Not specified

Equivalent Stress Equation:

$\text{Log } N_f = 18.60 - 7.92 \log (S_{eq})$
$S_{eq} = S_{max} (1-R)^{0.55}$
Standard Error of Estimate = 0.41
Standard Deviation in Life = 0.86
R^2 = 77%

Sample Size = 37

[Caution: The equivalent stress model may provide unrealistic life predictions for stress ratios beyond those represented above]

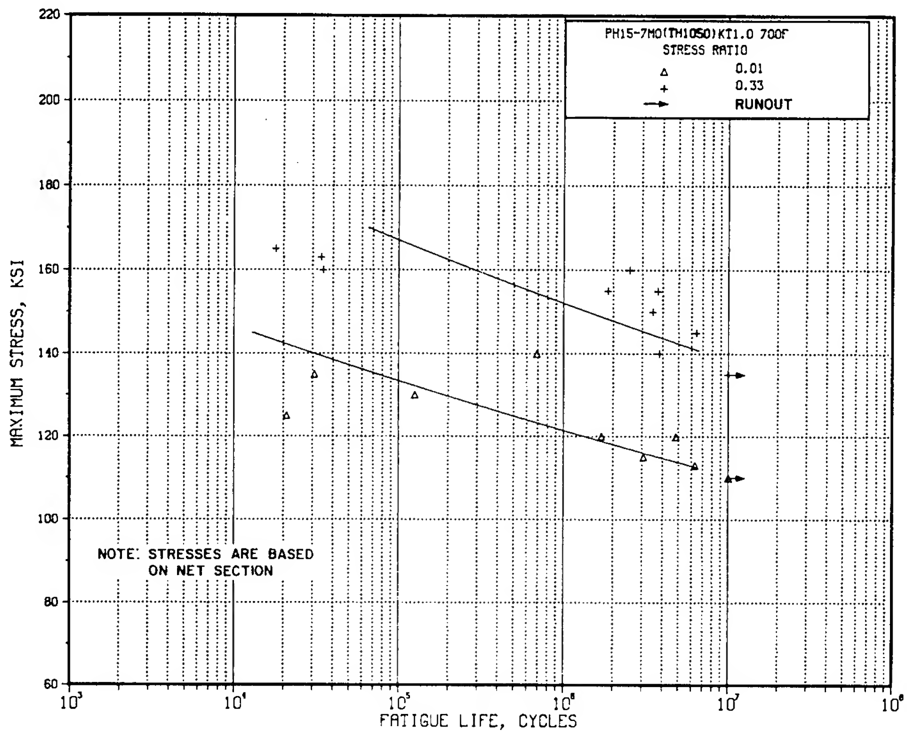

FIGURE 2.6.7.1.8(e). *Best-fit S/N curves for PH15-7Mo (TH1050) sheet at 700 F, transverse direction.*

Correlative Information for Figure 2.6.7.1.8(e)

Product Form: Sheet, 0.050-inch

Properties:	TUS, ksi	TYS, ksi	Temp., F
	175	161	700 (LT)

Specimen Details: Unnotched
2.0-inch gross width
0.375-inch net width

Surface Condition: Polished in longitudinal direction with wet 600 grit silicon carbide paper

Reference: 2.6.7.1.8(c)

Test Parameters:

Loading - Axial
Frequency - 1200 cpm
Temperature - 700 F
Environment - Air

No. of Heats/Lots: Not specified

Equivalent Stress Equation:

Log N_f = 56.92–24.46 log (S_{eq})
$S_{eq} = S_{max} (1-R)^{0.58}$
Standard Error of Estimate = 0.77
Standard Deviation in Life = 0.99
R^2 = 39%

Sample Size = 17

[Caution: The equivalent stress model may provide unrealistic life predictions for stress ratios beyond those represented above]

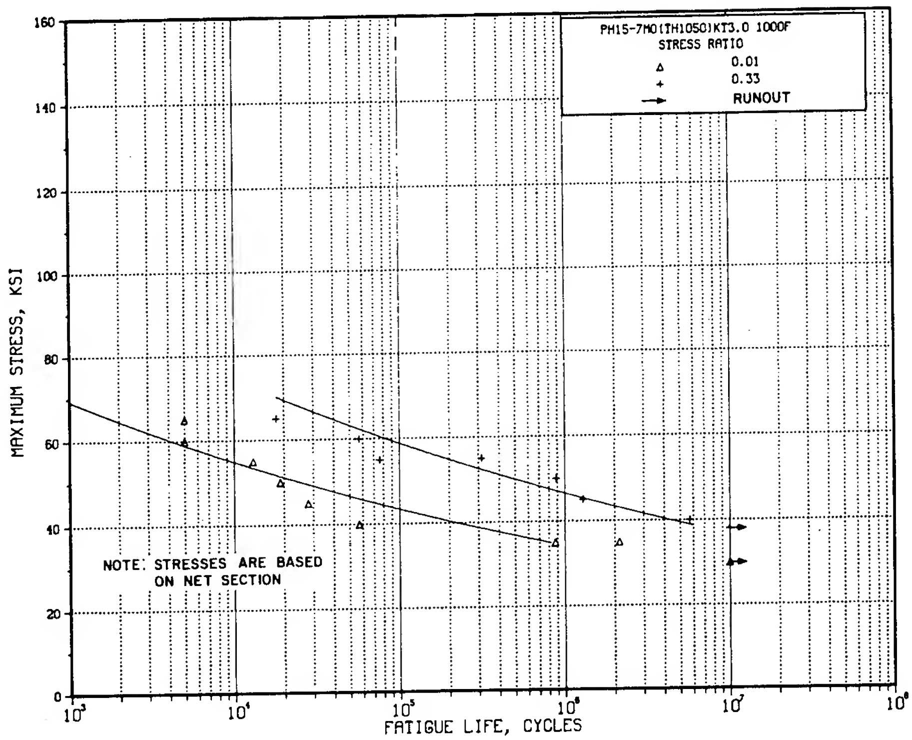

FIGURE 2.6.7.1.8(f). *Best-fit S/N curves for notched $K_t = 3.0$, PH15-7Mo (TH1050) sheet at 1000 F, transverse direction.*

Correlative Information for Figure 2.6.7.1.8(f)

Product Form: Sheet, 0.050 inch

Properties:	TUS, ksi	TYS, ksi	Temp., F
	88	88	1000 (LT)

Specimen Details: Edge Notched, $K_t = 3.0$
0.535-inch gross width
0.375-inch net width
0.021-inch notch radius
60° flank angle, ω

Surface Condition: Polished longitudinally

Reference: 2.6.7.1.8(c)

Test Parameters:

Loading – Axial
Frequency – 1200 cpm
Temperature – 1000 F
Environment – Air

No. of Heats/Lots: Not specified

Equivalent Stress Equation:

$\text{Log } N_f = 21.00 - 9.80 \log (S_{eq})$

$S_{eq} = S_{max} (1-R)^{0.78}$
Standard Error of Estimate = 0.33
Standard Deviation in Life = 0.99
$R^2 = 89\%$

Sample Size = 16

[Caution: The equivalent stress model may provide unrealistic life predictions for stress ratios beyond those represented above]

2.6.8 17-4PH

2.6.8.0 *Comments and Properties.*—Alloy 17-4PH is a precipitation-hardening, martensitic stainless steel used for parts requiring high strength and good corrosion and oxidation resistance up to 600 F. The alloy is available in all product forms.

Manufacturing Considerations.—17-4PH is readily forged, machined, welded, and brazed. Machining requires the same precautions as the austenitic stainless steels except that work-hardening is not a problem. Best machinability is exhibited by Conditions H1150 and H1150M. A dimensional contraction of 0.0004 to 0.0006 and 0.0008 to 0.0010 in./in. occurs upon hardening to the H900 and H1150 conditions, respectively. This fact should be considered before finish machining prior to aging treatment.

When permanent deformation is performed, such as cold straightening of hardened parts, reaging is recommended to minimize internal stresses.

Alloy 17-4PH can be fusion welded with any of the normal processes using 17-4PH filler metal without preheat. For details up to ½-inch thickness, Condition A is satisfactory prior to welding, but for heavy sections, an overaged condition (H1150) is recommended to preclude cracking. After welding, weldments should be aged or solution treated and aged.

Alloy 17-4PH castings are produced in sand molds, investment molds, and by centrifugal casting. While 17-4PH has good castability, it is subject to hot-tearing, so heavy X or T sections, sharp corners, and abrupt changes in section size should be avoided. Alloy 17-4PH castings are susceptible to microshrinkage which will decrease the ductility but have no effect on the yield or ultimate strength. During heat treatment, care must be exercised to avoid carbon or nitrogen contamination from furnace atmospheres. Combusted hydrocarbon and dissociated ammonia atmospheres have been sources of contamination. Air is commonly used and both vacuum and dry argon are effective for minimizing scaling. Oxides formed during solution treating in air may be removed by grit blasting or abrasive tumbling.

Alloy 17-4PH can be heat treated to develop a wide range of properties. Heat treatment procedures are specified in applicable material specifications and MIL-H-6875.

Design and Environmental Considerations.—For tensile applications where stress corrosion is a possibility, 17-4PH should be aged at the highest temperature compatible with strength requirements and at a temperature not lower than 1025 F for 4 hours minimum.

The impact strength of 17-4PH, especially large size bar in the H900 and H925 conditions, may be very low at subzero temperatures; consequently, the use of 17-4PH for critical applications at low temperatures should be avoided. For non-impact applications, such as valve seats, parts in the H925 condition have performed satisfactorily down to -320 F. The H1100 and H1150 conditions have improved impact strength so that parts made from small diameter bar can be used down to -100 F with low risk. For critical low temperature applications, a similar alloy, 15-5PH (consumable electrode vacuum melted), should be used instead of 17-4PH because of its superior impact strength at low temperature.

Specifications and Properties.—Material specifications for 17-4PH are presented in Table 2.6.8.0(a). Room temperature mechanical and physical properties for various conditions of 17-4PH products are presented in Table 2.6.8.0(b) through (f). The physical properties of this alloy at room and elevated temperatures are presented in Figure 2.6.8.0.

TABLE 2.6.8.0(a). *Material Specifications for 17-4PH Stainless Steel*

Specification	Form
AMS 5604	Sheet, strip, and plate
AMS 5643	Bar, forging, and ring
AMS 5342	Investment casting (H1100)
AMS 5343	Investment casting (H1000)
AMS 5344	Investment casting (H900)

2.6.8.1 *H900 Condition*.—Elevated temperature curves for various mechanical properties are presented in Figures 2.6.8.1.2 through 2.6.8.1.4. Unnotched and notched fatigue information at room temperature is presented in Figures 2.6.8.1.8(a) through (c).

2.6.8.2 *Various Heat Treat Conditions*.—Elevated temperature curves for tensile yield and ultimate strengths are depicted in Figure 2.6.8.2.1. Room temperature stress-strain and tangent-modulus curves are shown in Figures 2.6.8.2.6(a) and (b).

2.6.8.3 *H1000 Condition*.—Room temperature stress-strain and tangent-modulus curves for castings are shown in Figures 2.6.8.3.6(a) and (b).

2.6.8.4 *H1025 Condition*.—Notched fatigue information is presented in Figure 2.6.8.4.8 for bar.

2.6.8.5 *H1100 Condition*.—Notched fatigue information is presented in Figure 2.6.8.5.8 for bar.

2.6.8.6 *H1150 Condition*.—Elevated temperature curves for tensile yield and ultimate strengths are shown in Figure 2.6.8.6.1.

TABLE 2.6.8.0(b). *Design Mechanical and Physical Properties of 17-4PH Stainless Steel Sheet, Strip, and Plate*

Specification	AMS 5604					
Form	Sheet, strip[a], and plate					
Condition	H900	H925	H1025	H1075	H1100	H1150
Thickness, in.	≤ 4.000					
Basis	S	S	S	S	S	S
Mechanical Properties:						
F_{tu}, ksi:						
L	...	...	...	...	...	...
LT	190	170	155	145	140	135
F_{ty}, ksi:						
L	...	...	...	...	...	...
LT	170	155	145	125	115	105
F_{cy}, ksi:						
L	...	...	...	...	...	...
LT	...	...	...	...	...	...
F_{su}, ksi	...	...	...	...	...	...
F_{bru}, ksi:						
(e/D = 1.5)	...	...	...	...	...	...
(e/D = 2.0)	...	...	...	...	...	...
F_{bry}, ksi:						
(e/D = 1.5)	...	...	...	...	...	...
(e/D = 2.0)	...	...	...	...	...	...
e, percent:						
LT	b	b	b	b	b	b
E, 10^3 ksi	28.5					
E_c, 10^3 ksi	30.0					
G, 10^3 ksi	11.2					
μ	0.27					
Physical Properties:						
ω, lb/in.^{3}	0.282 (H900), 0.283 (H1075), 0.284 (H1150)					
C, K, and α	See Figure 2.6.8.0					

[a]Test direction longitudinal for widths less than 9 inches; long transverse for widths 9 inches and over.
[b]See Table 2.6.8.0(c).

TABLE 2.6.8.0(c). *Minimum Elongation Values for 17-4PH Sheet, Strip, and Plate*

Thickness	e, percent (LT)					
	H900	H925	H1025	H1075	H1100	H1150
0.015 through 0.186	5	5	5	5	5	8
0.187 through 0.625	8	8	8	9	10	10
0.626 through 4.000	10	10	12	13	14	16

TABLE 2.6.8.0(d). *Design Mechanical and Physical Properties of 17-4PH Stainless Steel Forging, Tubing, and Rings*

Specification	AMS 5643						
Form	Forging, tubing, and rings						
Condition	H900	H925	H1025	H1075	H1100	H1150	H1150M[a]
Thickness, in.	<8.000						
Basis	S	S	S	S	S	S	S
Mechanical Properties:							
F_{tu}, ksi:							
L	190	170	155	145	140	135	115
T	...	...	...	...	...	...	...
F_{ty}, ksi:							
L	170	155	145	125	115	105	75
T	...	...	...	...	...	...	...
F_{cy}, ksi:							
L	...	...	...	...	...	...	...
T	...	...	...	...	...	...	...
F_{su}, ksi	...	...	...	...	...	...	...
F_{bru}, ksi:							
(e/D = 1.5)	...	...	...	...	...	...	...
(e/D = 2.0)	...	...	...	...	...	...	...
F_{bry}, ksi:							
(e/D = 1.5)	...	...	...	...	...	...	...
(e/D = 2.0)	...	...	...	...	...	...	...
e, percent:							
L	10	10	12	13	14	16	18
E, 10^3 ksi	28.5						
E_c, 10^3 ksi	30.0						
G, 10^3 ksi	11.2						
μ	0.27						
Physical Properties:							
ω, lb/in.^{3}	0.282 (H900), 0.283 (H1075), 0.284 (H1150)						
C, K, and α	See Figure 2.6.8.0						

[a]Not covered by AMS 5643. S values are producers' guaranteed minimum tensile properties.

TABLE 2.6.8.0(e). *Design Mechanical and Physical Properties of 17-4PH Stainless Steel Bar*

Specification	AMS 5643										
Form	Bar										
Condition	H900		H925		H1025	H1075		H1100	H1150		H1150M[a]
Thickness or diameter, in.	<8.000										
Basis	A	B	A	B	S	A	B	S	A	B	S[a]
Mechanical Properties:[e]											
F_{tu}, ksi:											
L	190	195	170	178	155	143	150	140	125	134	115
T	...	...	...	...	...	...	...	...	...	...	...
F_{ty}, ksi:											
L	170	175	155[b]	167	145	125[c]	143	115	100	115	75
T	...	...	...	...	...	...	...	...	...	...	...
F_{cy}, ksi:											
L	170	175	...	...	139	...	...	...	90	104	...
T	...	...	...	...	...	...	...	...	...	...	...
F_{su}, ksi	123	126	...	...	95	...	...	...	79	85	...
F_{bru}, ksi:											
(e/D = 1.5)	313	322	...	...	263[d]	...	...	...	213[d]	228[d]	...
(e/D = 2.0)	380	390	...	...	332[d]	...	...	...	270[d]	289[d]	...
F_{bry}, ksi:											
(e/D = 1.5)	255	262	...	...	211[d]	...	...	...	152[d]	175[d]	...
(e/D = 2.0)	280	288	...	...	250[d]	...	...	...	181[d]	208[d]	...
e, percent (S-basis):											
L	10	...	10	...	12	13	...	14	16	...	18
E, 10^3 ksi	28.5										
E_c, 10^3 ksi	30.0										
G, 10^3 ksi	11.2										
μ	0.27										
Physical Properties:											
ω, lb/in.^{3}	0.282 (H900), 0.283 (H1075), 0.284 (H1150)										
C, K, and α	See Figure 2.6.8.0										

[a]Not covered by AMS 5643. S values are producer's guaranteed minimum tensile properties.
[b]S-basis. A value = 157 ksi.
[c]S-basis. A value = 136 ksi.
[d]Bearing values are "dry pin" values per Section 1.4.7.1.
[e]Design allowables were based upon data from samples of material, supplied in the solution treated condition, which were aged to demonstrate response to heat treatment by suppliers.

TABLE 2.6.8.0(f). *Design Mechanical and Physical Properties of 17-4PH Stainless Steel Investment Casting*

Specification	AMS 5344	AMS 5343	AMS 5342
Form	Investment Casting		
Condition	a	H1000[b]	H1100[c]
Location within casting	Any area		
Basis	S	S	S
Mechanical Properties[d]:			
F_{tu}, ksi	180	150	130
F_{ty}, ksi	160	130	120
F_{cy}, ksi	...	132	...
F_{su}, ksi	...	98	...
F_{bru}[e], ksi:			
(e/D = 1.5)	...	254	...
(e/D = 2.0)	...	329	...
F_{bry}[e], ksi:			
(e/D = 1.5)	...	189	...
(e/D = 2.0)	...	222	...
e, percent	4	4	6
RA, percent	12	12	15
E, 10^3 ksi	28.5		
E_c, 10^3 ksi	30.0		
G, 10^3 ksi	12.7		
μ	0.27		
Physical Properties:			
ω, lb/in.^{3}	0.282 (H900)		
C, K, and α	See Figure 2.6.8.0		

[a]Aged at 900 to 925F for 90 minutes.
[b]Aged at 985 to 1015 F for 90 minutes.
[c]Aged at 1085 to 1115 F for 90 minutes.
[d]Properties apply only when drawing specifies that conformance to tensile property requirements shall be determined from specimens cut from casting or integrally cast specimens.
[e]Bearing values are "dry pin" values per Section 1.4.7.1.

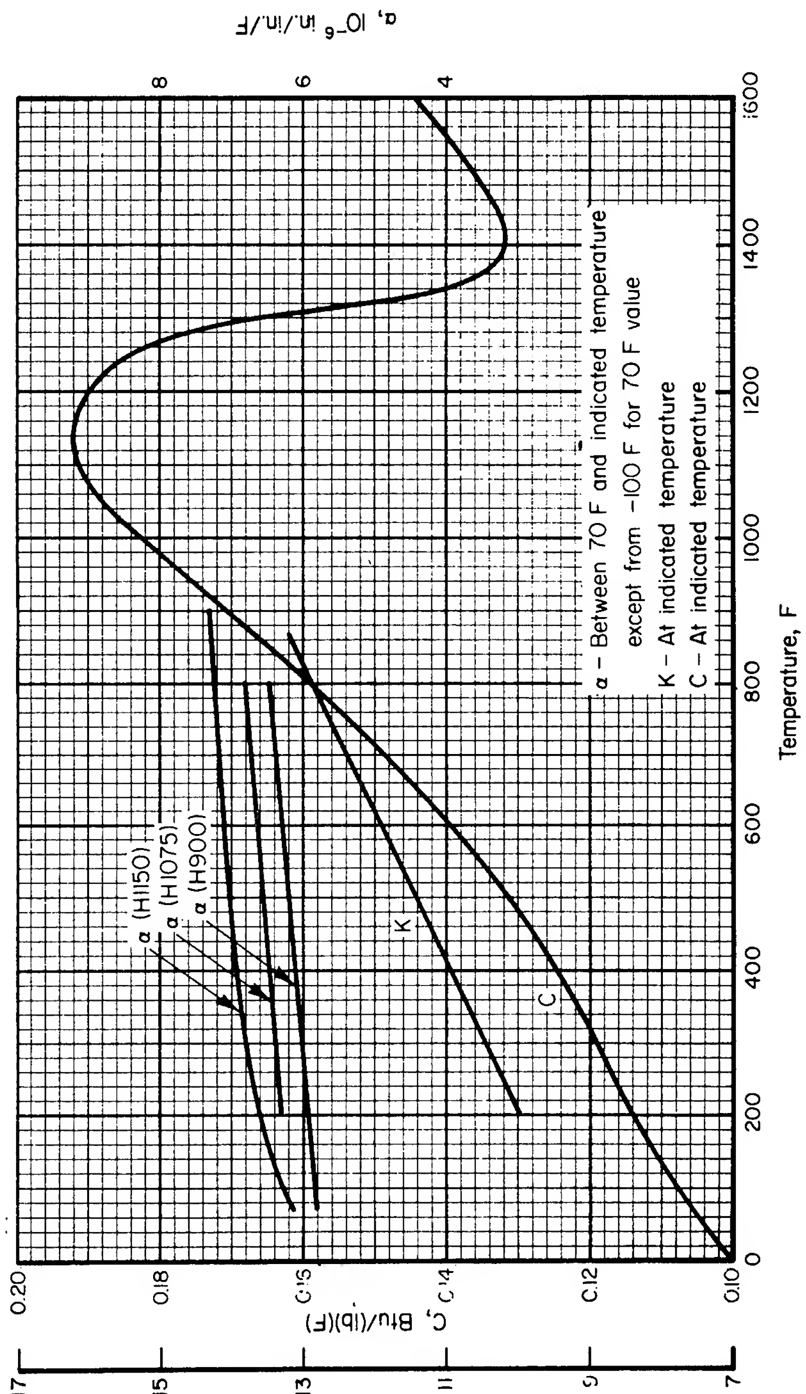

FIGURE 2.6.8.0. *Effect of temperature on the physical properties of 17-4 PH stainless steel.*

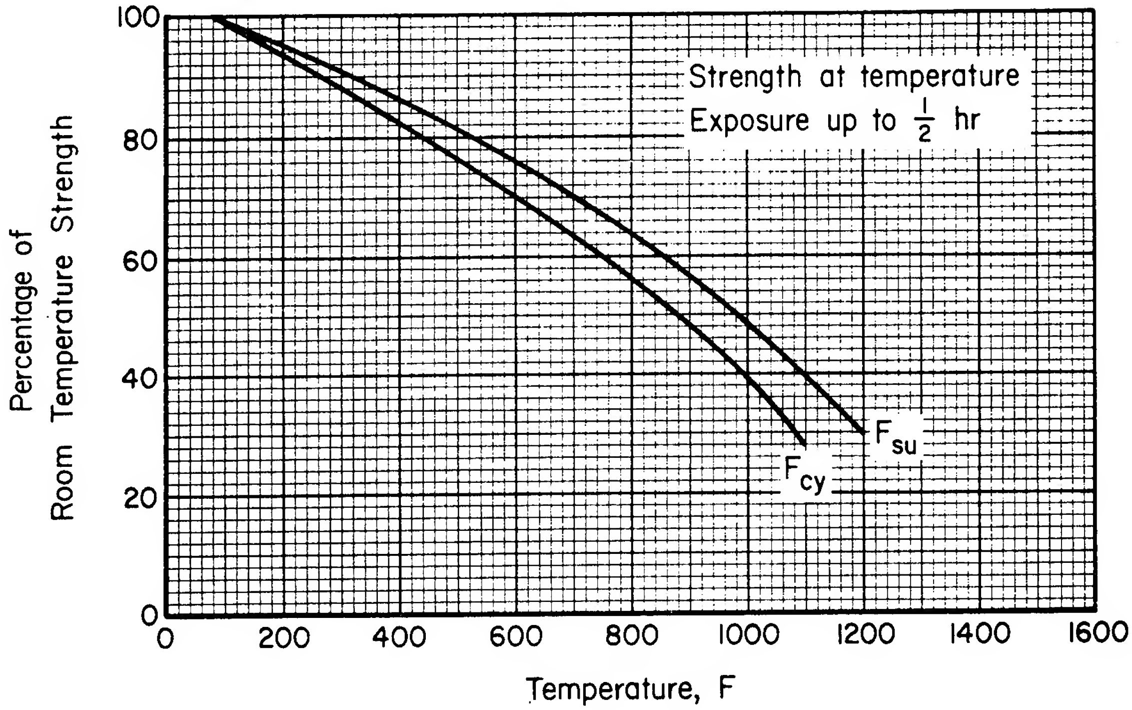

FIGURE 2.6.8.1.2. *Effect of temperature on the compressive yield strength (F_{cy}) and the shear ultimate strength (F_{su}) of 17-4PH (H900) stainless steel bar and forging.*

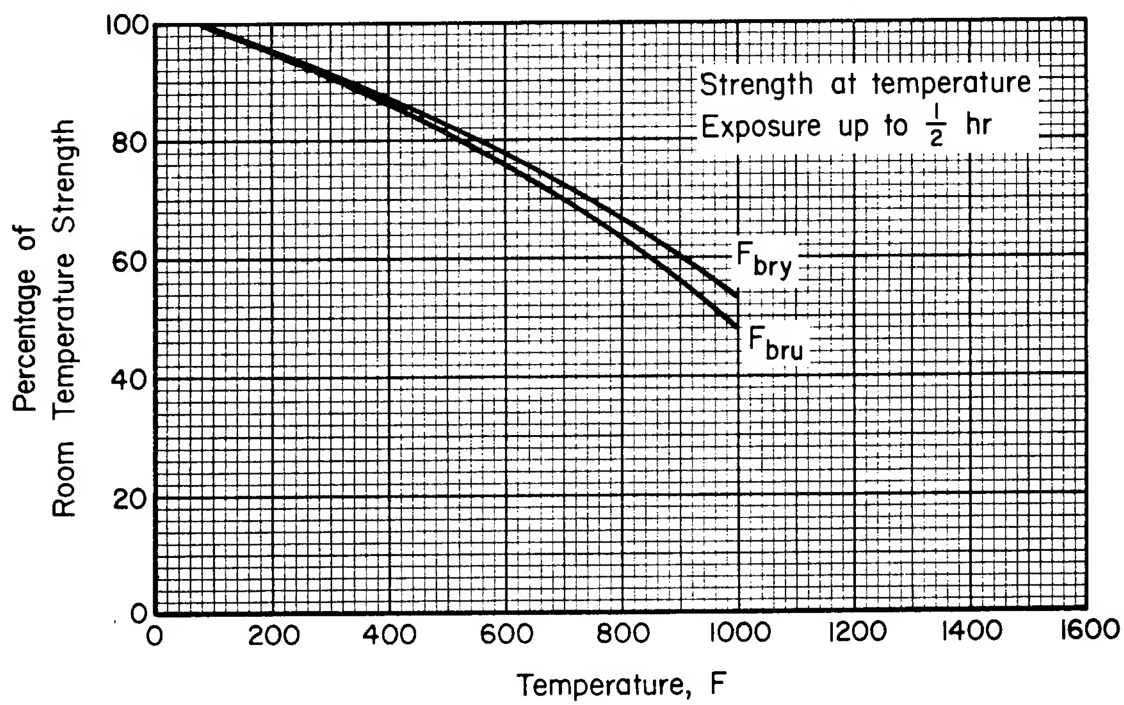

FIGURE 2.6.8.1.3. *Effect of temperature on the bearing ultimate strength (F_{bru}) and the bearing yield strength (F_{bry}) of 17-4PH (H900) stainless steel bar and forging.*

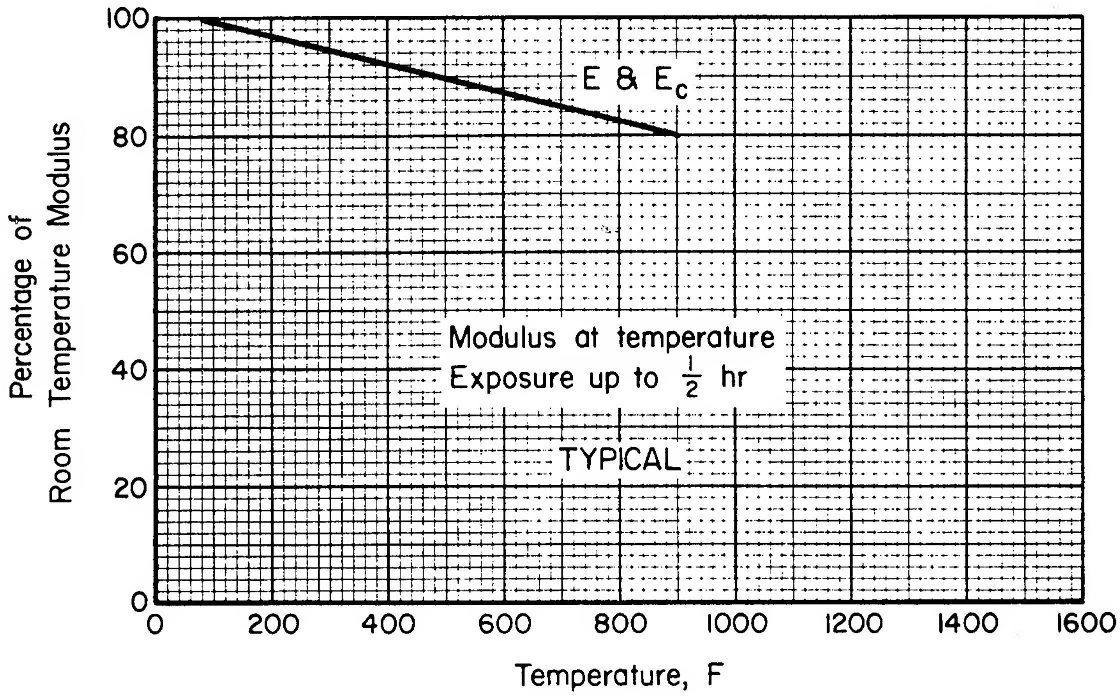

FIGURE 2.6.8.1.4. *Effect of temperature on the tensile and compressive moduli (E and E_c) of 17-4 PH (H900) stainless steel bar and forging.*

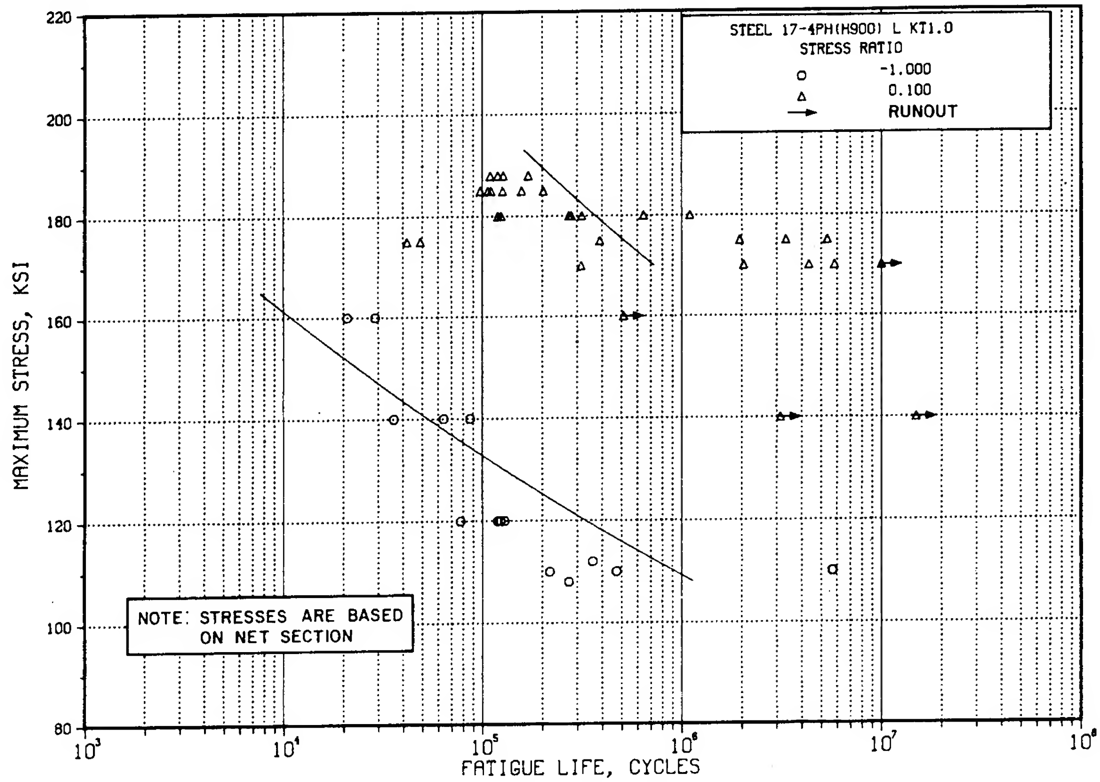

FIGURE 2.6.8.1.8(a). *Best-fit S/N curves for unnotched 17-4PH (H900) bar, longitudinal direction.*

Correlative Information for Figure 2.6.8.1.8(a)

Product Form: Bar, 1-inch and 1⅛-inch diameter

Properties:

TUS, ksi	TYS, ksi	Temp., F
202	195	RT

Specimen Details: Unnotched
1.25-inch gross diameter
0.252-inch net diameter

Surface Condition: Polished

Reference: 2.6.8.1.8(a)

Test Parameters:

Loading – Axial
Frequency – 1800 cpm
Temperature – RT
Environment – Air

No. of Heats/Lots: Not specified

Equivalent Stress Equation:

Log N_f = 30.6–11.2 log (S_{eq})
$S_{eq} = S_{max} (1\text{-}R)^{0.52}$
Standard Error of Estimate = 0.531
Standard Deviation in Life = 0.672
R^2 = 38%

Sample Size = 42

[Caution: The equivalent stress model may provide unrealistic life predictions for stress ratios beyond those represented above]

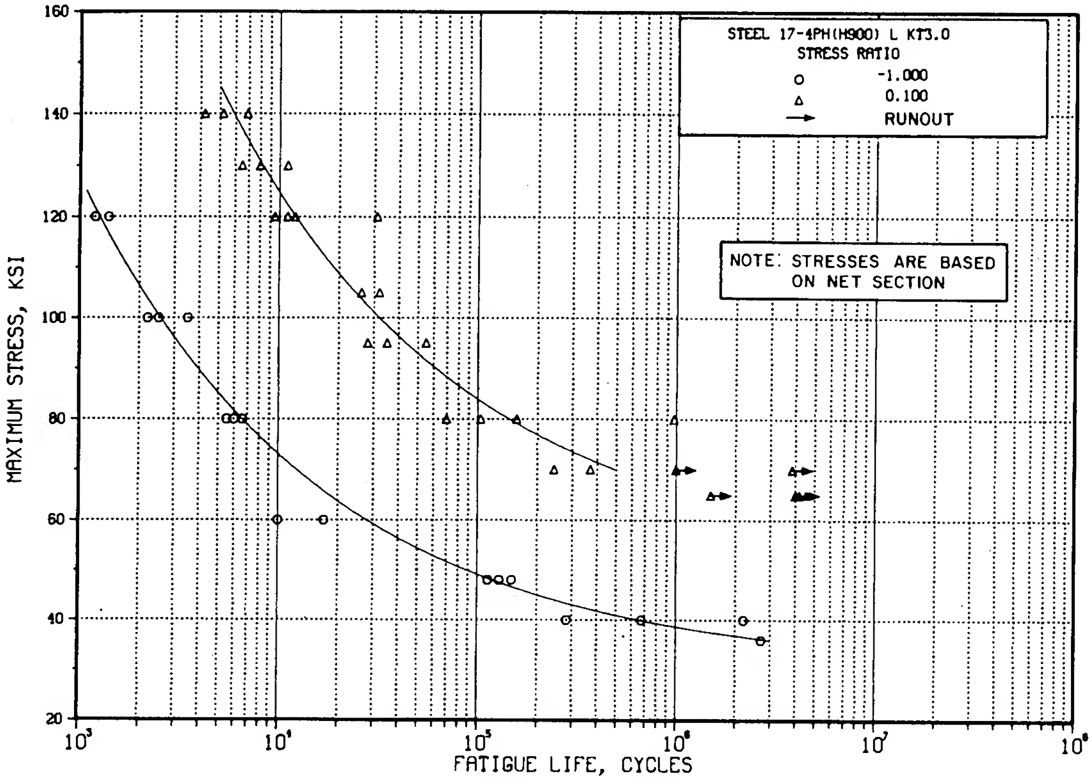

FIGURE 2.6.8.1.8(b). *Best-fit S/N curves for notched K_t = 3.0, 17-4PH (H900) bar, longitudinal direction.*

Correlative Information for Figure 2.6.8.1.8(b)

Product Form: Bar, 1-inch and 1⅛-inch diameter

Properties:	TUS, ksi	TYS, ksi	Temp., F
	202	195	RT

Specimen Details: Circumferential V-Groove, K_t = 3.0

Gross diameter inches	Net diameter inches	Notch radius inches
0.430	0.300	0.016
0.357	0.252	0.013

60° flank angle, ω

Surface Condition: Polished

Reference: 2.6.8.1.8(a)

Test Parameters:

Loading – Axial
Frequency – Not specified
Temperature – RT
Environment – Air

No. of Heats/Lots: Not specified

Equivalent Stress Equation:

Log N_f = 9.10–2.79 log (S_{eq} – 48.4)
$S_{eq} = S_{max} (1\text{-}R)^{0.67}$
Standard Error of Estimate = 0.235
Standard Deviation in Life = 0.897
R^2 = 93%

Sample Size = 39

[Caution: The equivalent stress model may provide unrealistic life predictions for stress ratios beyond those represented above]

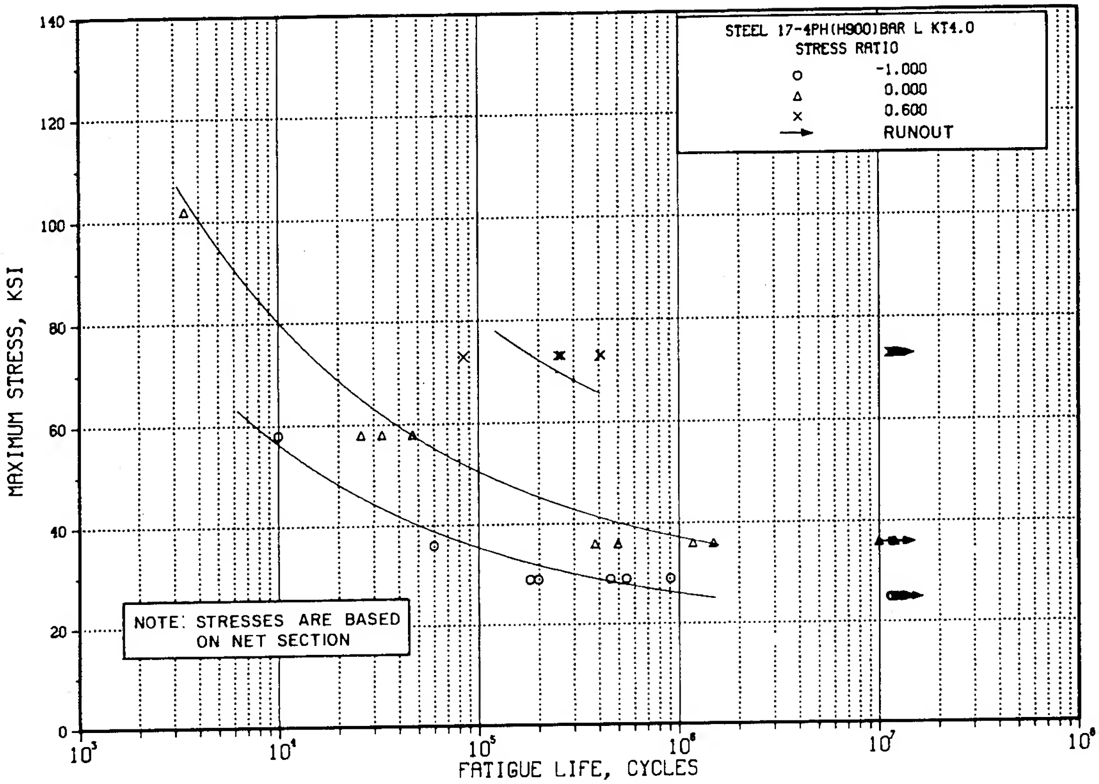

FIGURE 2.6.8.1.8(c). *Best-fit S/N curves for notched K_t = 4.0, 17-4PH (H900) bar, longitudinal direction.*

Correlative Information for Figure 2.6.8.1.8(c)

Product Form: Bar, 0.787-inch diameter, vacuum melted

Properties:

TUS, ksi	TYS, ksi	Temp., F
207	—	RT

Specimen Details: Circumferential V-Groove, K_t = 4.0

0.492-inch gross diameter
0.256-inch net diameter
0.008-inch notch radius, n
60° flank angle, ω

Surface Condition: Machined and aged

Reference: 2.6.8.1.8(b)

Test Parameters:

Loading - Axial
Frequency - 2000 cpm
Temperature - RT
Environment - Air

No. of Heats/Lots: 1

Equivalent Stress Equation:

Log N_f = 9.03–2.91 log (S_{eq} – 26.1)
$S_{eq} = S_{max} (1\text{-}R)^{0.51}$
Standard Error of Estimate = 0.345
Standard Deviation in Life = 0.812
R^2 = 82%

Sample Size = 22

[Caution: The equivalent stress model may provide unrealistic life predictions for stress ratios beyond those represented above]

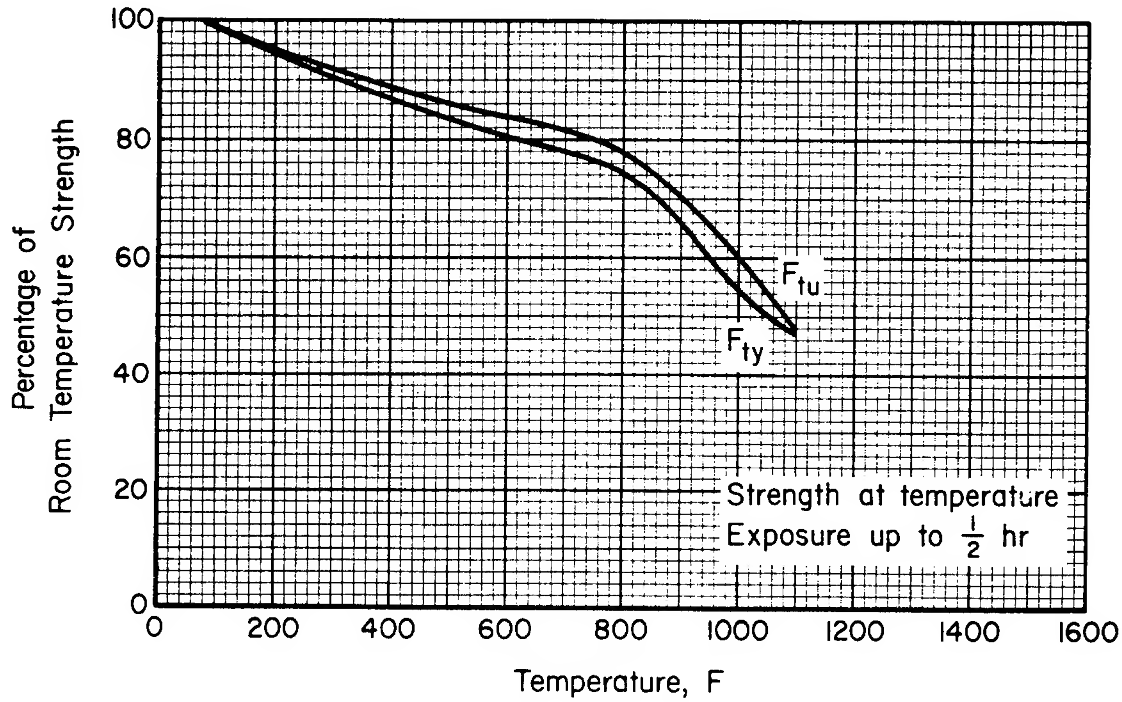

FIGURE 2.6.8.2.1. *Effect of temperature on the tensile ultimate strength (F_{tu}) and the tensile yield strength (F_{ty}) of 17-4PH (H900, H925, H1025, and H1075) stainless steel bar.*

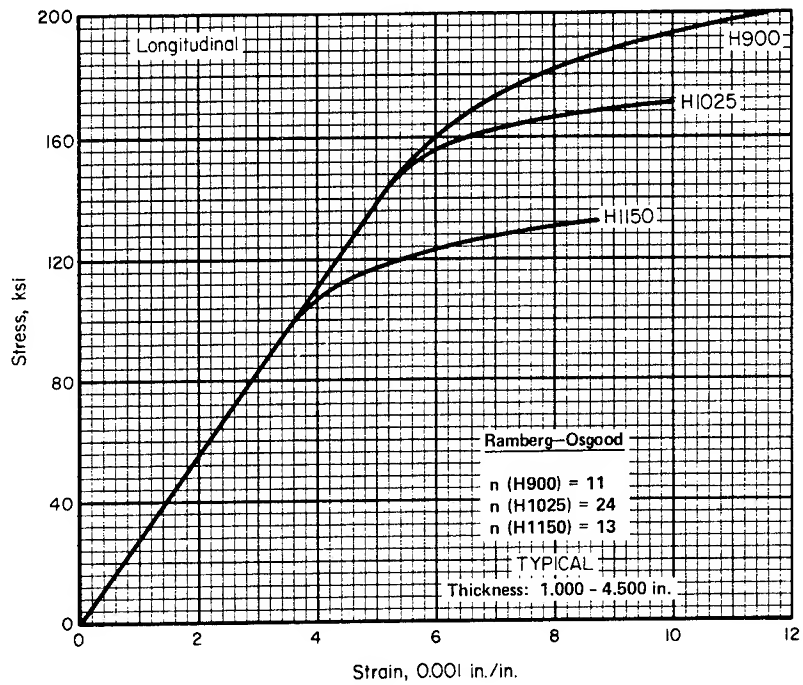

FIGURE 2.6.8.2.6(a). *Typical tensile stress-strain curves at room temperature for various heat treated conditions of 17-4PH stainless steel bar.*

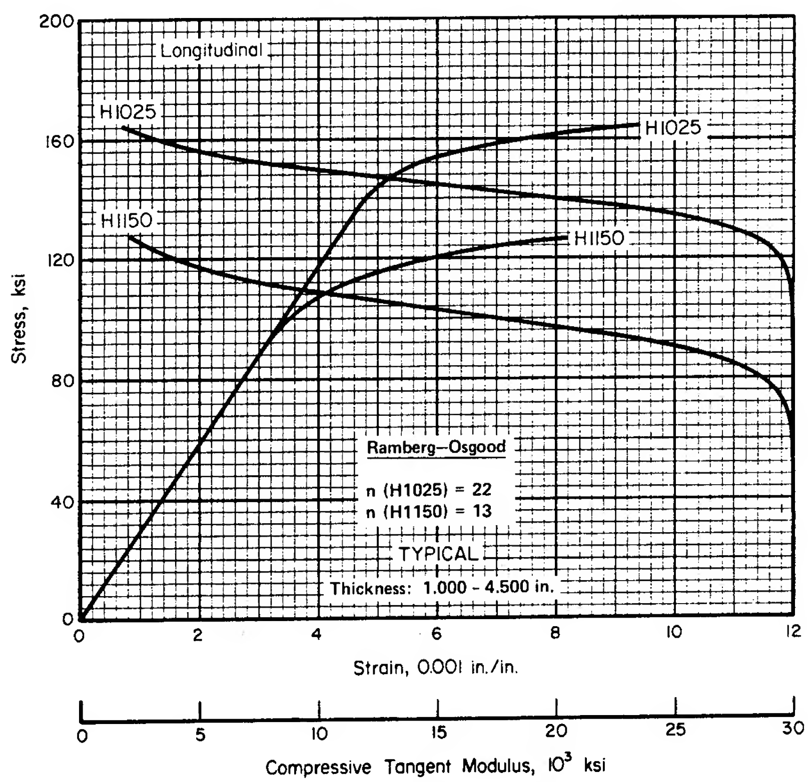

FIGURE 2.6.8.2.6(b). *Typical compressive stress-strain and compressive tangent-modulus curves at room temperature for various heat treated conditions of 17-4PH stainless steel bar.*

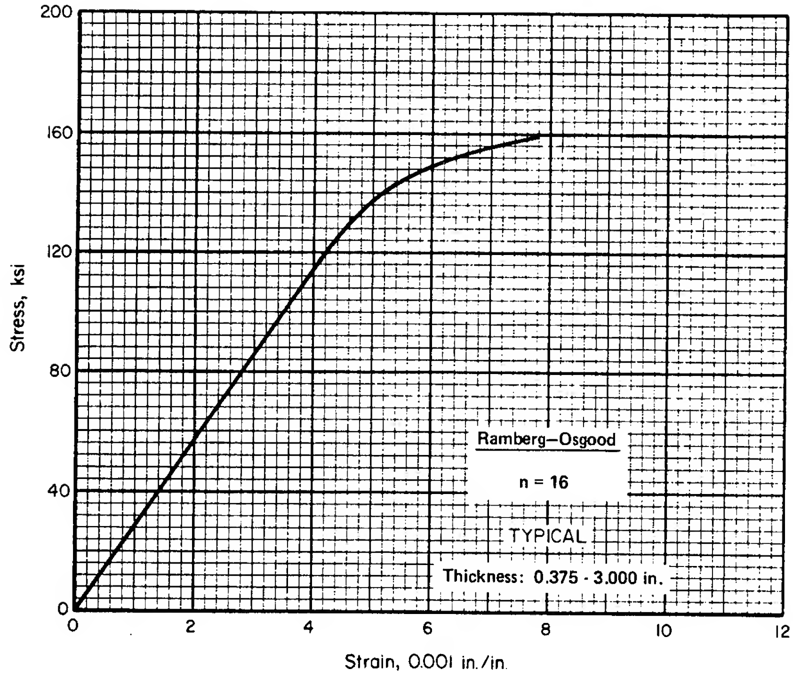

FIGURE 2.6.8.3.6(a). *Typical tensile stress-strain curve for 17-4PH (H1000) stainless steel casting at room temperature.*

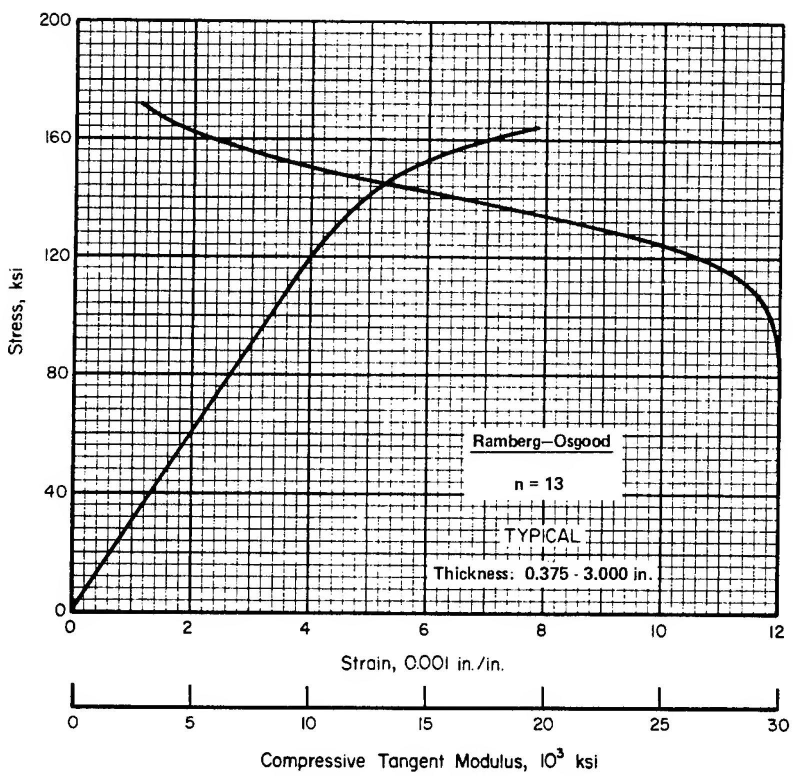

FIGURE 2.6.8.3.6(b). *Typical compressive stress-strain and compressive tangent-modulus curves for 17-4PH (H1000) stainless steel casting at room temperature.*

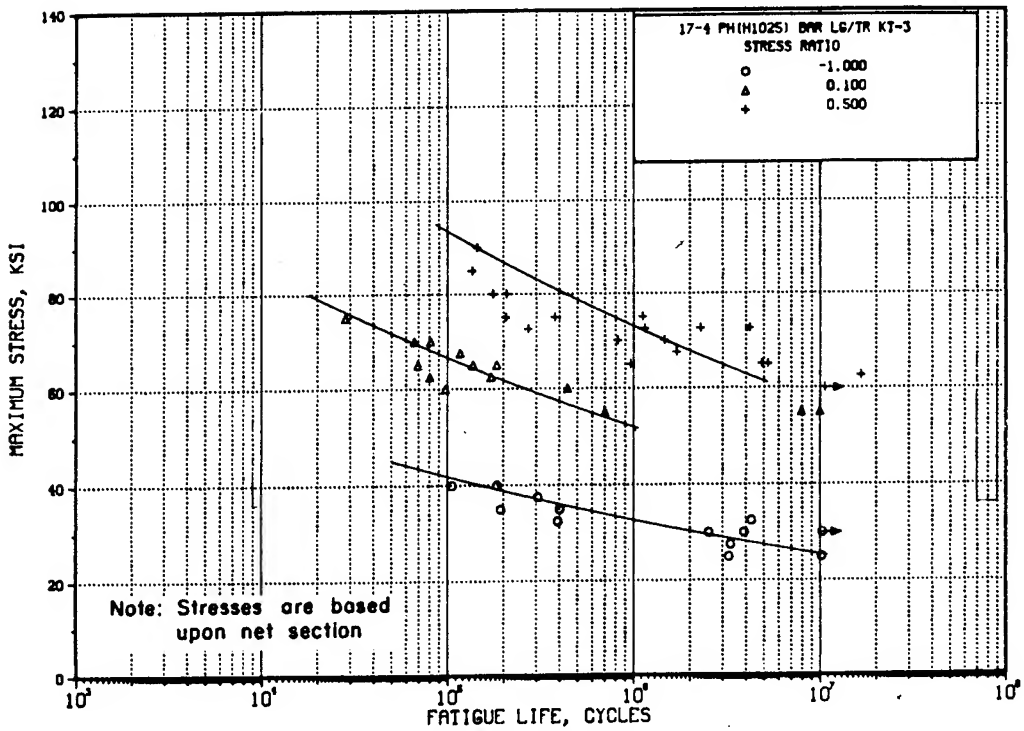

FIGURE 2.6.8.4.8. *Best-fit S/N curves for notched K_t = 3.0, fatigue behavior of 17-4PH (H1025) stainless steel bar, longitudinal and long transverse directions.*

Correlative Information for Figure 2.6.8.4.8

Product Form: Bar, 2 x 6 inches

Properties:	TUS, ksi	TYS, ksi	Temp., F
Longitudinal	165	161	RT
Long Transverse	164	158	RT
Longitudinal	280	—	RT (notched)
Long Transverse	275	—	RT (notched)

Specimen Details: Notched V-Groove,
K_t = 3.0
0.375-inch gross diameter
0.250-inch net diameter
0.013-inch root radius, r
60° flank angle, ω

Surface Condition: Notched: Ground notch

Reference: 2.6.6.2.8

Test Parameters:

Loading – Axial
Frequency – 1800 cpm
Temperature – RT
Environment – Air

No. of Heats/Lots: 3

Equivalent Stress Equation:

Log N_f = 21.60–9.24 log (S_{eq})
$S_{eq} = S_{max} (1-R)^{0.581}$
Standard Error of Estimate = 0.413
Standard Deviation in Life = 0.724
R^2 = 67%

Sample Size = 44

[Caution: The equivalent stress model may provide unrealistic life predictions for stress ratios beyond those represented above]

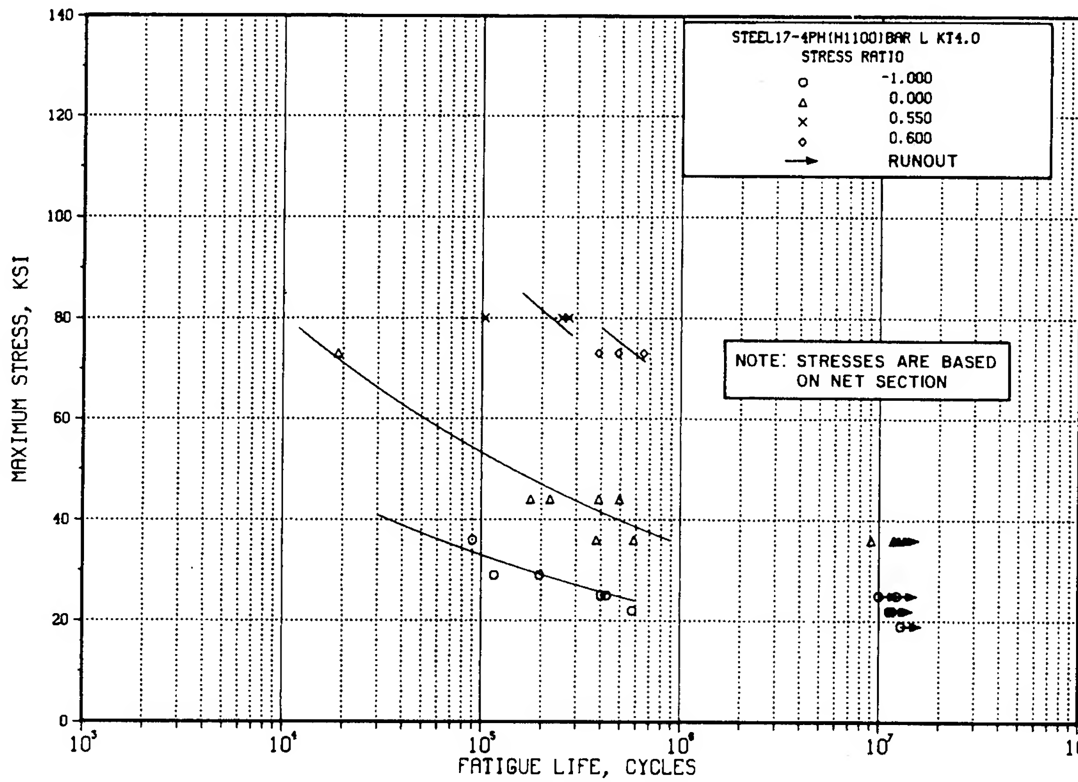

FIGURE 2.6.8.5.8. *Best-fit S/N curves for notched K_t = 4.0, 17-4PH (H1100) bar, longitudinal direction.*

Correlative Information for Figure 2.6.8.5.8

Product Form: Bar, 0.787-inch diameter

Properties:	TUS, ksi	TYS, ksi	Temp., F
	151	—	RT

Specimen Details: Circumferential V-Groove, K_t = 4.0

0.492-inch gross diameter
0.256-inch net diameter
0.008-inch notch radius, r
60° flank angle, ω

Surface Condition: Machined then aged

Reference: 2.6.8.1.8(b)

Test Parameters:

Loading - Axial
Frequency - 2000 cpm
Temperature - RT
Environment — Air

No. of Heats/Lots:

Equivalent Stress Equation:

$\text{Log } N_f = 14.6 - 5.56 \log (S_{eq})$
$S_{eq} = S_{max} (1-R)^{0.69}$
Standard Error of Estimate = 0.301
Standard Deviation in Life = 0.556
R^2 = 71%

Sample Size = 21

[Caution: The equivalent stress model may provide unrealistic life predictions for stress ratios beyond those represented above]

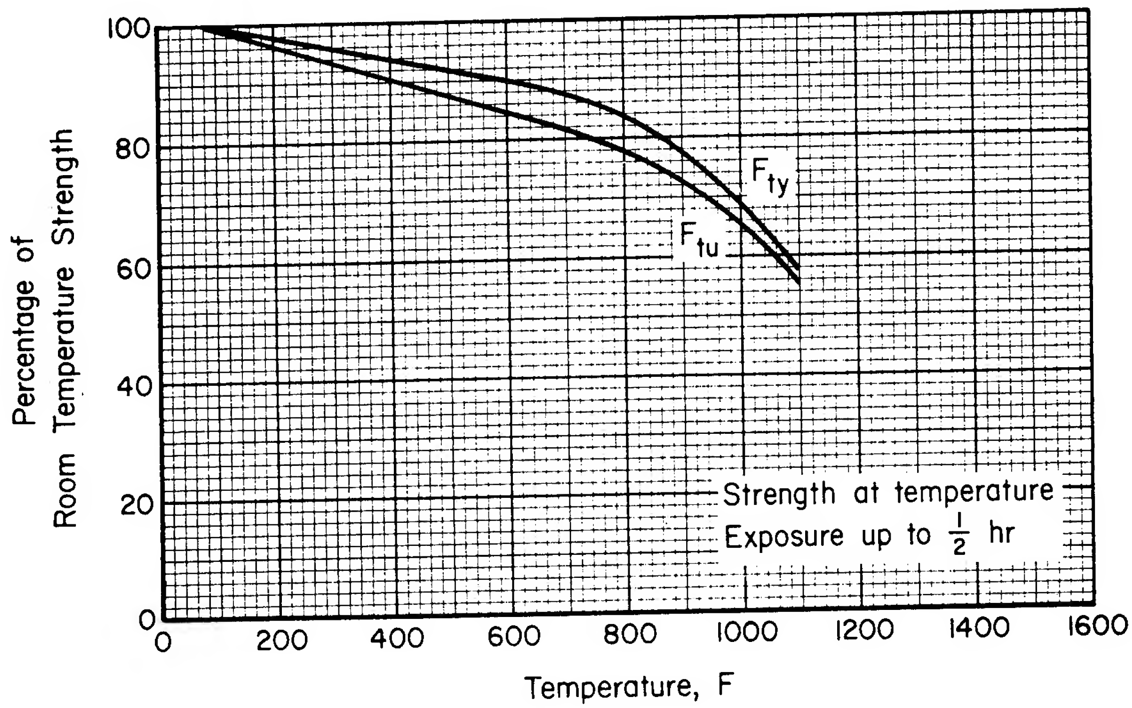

FIGURE 2.6.8.6.1. *Effect of temperature on the tensile ultimate strength (F_{tu}) and the tensile yield strength (F_{ty}) of 17-4PH (H1150) stainless steel bar.*

2.6.9 17-7PH

2.6.9.0 *Comments and Properties.*—17-7PH is a semiaustenitic stainless steel used where high strength and good corrosion and oxidation resistance are needed up to 600 F. This steel is supplied in Condition A for ease of forming.

Manufacturing Considerations.—17-7PH in Condition A is readily cold formed. Conventional inert-gas shielded arc and resistance techniques are generally used for welding. Vapor blasting of scaled Condition TH1050 parts is recommended because of the hazards of intergranular corrosion during pickling operations.

Heat Treatment.—17-7PH must be used in the heat-treated condition and should not be placed in service in Condition A or T. Condition A should be restored by resolution treating when this condition has been altered during processing operations such as hot working, welding, or brazing. The heat-treatment procedures for this steel are compatible with the cycles, used for honeycomb panel brazing. In hardening this steel from Condition A to Condition TH1050 a net dimensional growth of 0.0045 in./in. will occur.

The heat treatment to anneal is:

Treatment	Designation
1950 ± 25 F and air cool	Condition A

The transformation treatment from Condition A is as follows:

Treatment	Designation
1400 ± 25 F - 90 minutes and cool to 55 ± 5 F for 30 minutes	Condition T

The aging treatment is:

Treatment	Designation
1050 ± 10 F - 90 minutes and air cool	TH1050

Environmental Considerations.—The resistance of 17-7PH to stress-corrosion cracking in chloride environs has been evaluated and found to be superior to that of the alloy steels and the hardenable chromium steels. Strength properties are lowered by exposure to temperatures above about 975 F for periods longer than one-half hour.

Specifications and Properties.—Material specifications for 17-7PH stainless steel is presented in Table 2.6.9.0(a). The room-temperature properties of 17-7PH are shown in Tables 2.6.9.0(b) and (c). The effect of temperature on the physical properties of this alloy are presented in Figure 2.6.9.0.

TABLE 2.6.9.0(a). *Material Specification for 17-7PH Stainless Steel*

Specification	Form
AMS 5528	Plate, sheet, and strip
MIL-S-25043	Plate, sheet, and strip

2.6.9.1 *TH1050 Condition.*—Elevated temperature curves for various mechanical properties are presented in Figures 2.6.9.1.1, 2.6.9.1.2, and 2.6.9.1.4(a) and (b). Tensile and compression stress-strain curves at room temperature and at several elevated temperatures are presented in Figures 2.6.9.1.6(a) and (b). Typical compressive tangent-modulus curves at various temperatures are presented in Figure 2.6.9.1.6(c).

TABLE 2.6.9.0(b). *Design Mechanical and Physical Properties of 17-7PH Stainless Steel Sheet and Plate*

Specification	AMS 5528 and MIL-S-25043			AMS 5528
Form	Sheet		Plate	
Condition	TH1050			
Thickness, in.	0.015-0.187		0.188-0.500	0.501-1.000
Basis	A	B	S	S
Mechanical Properties:[a]				
F_{tu}, ksi:				
L	177	183	...	...
LT	177	184	180	180
F_{ty}, ksi:				
L	150[b]	167	...	...
LT	150[c]	167	150	150
F_{cy}, ksi:				
L	160	179	160	...
LT	166	185	166	...
F_{su}, ksi	112	117	114	...
F_{bru}, ksi:				
(e/D = 1.5)	305	317	310	...
(e/D = 2.0)	351	365	357	...
F_{bry}, ksi:				
(e/D = 1.5)	228	254	228	...
(e/D = 2.0)	240	267	240	...
e, percent (S-basis):				
LT	d,e	...	6[e]	6
E, 10^3 ksi	29.0			
E_c, 10^3 ksi	30.0			
G, 10^3 ksi	11.5			
μ	0.28			
Physical Properties:				
ω, lb/in.^{3}	0.276			
C, K, and α	See Figure 2.6.9.0			

[a]Design allowables were based upon data from samples of material, supplied in the solution treated condition, which were austenite conditioned and aged to demonstrate response to heat treatment by suppliers. Properties obtained by the user may be different if the material has been formed or otherwise cold worked.
[b]The A value of 158 ksi was reduced to agree with transverse specification value.
[c]S-basis. The A value equals 159 ksi.
[d]See Table 2.6.9.0(c).
[e]For MIL-S-25043, elongation values may be different than those presented.

TABLE 2.6.9.0(c). *Minimum Elongation Values for 17-7PH (TH1050) Stainless Steel Sheet*

Thickness, in.	Elongation (LT), percent
0.005 to 0.010	4
0.011 to 0.019	5
0.020 to 0.187	6

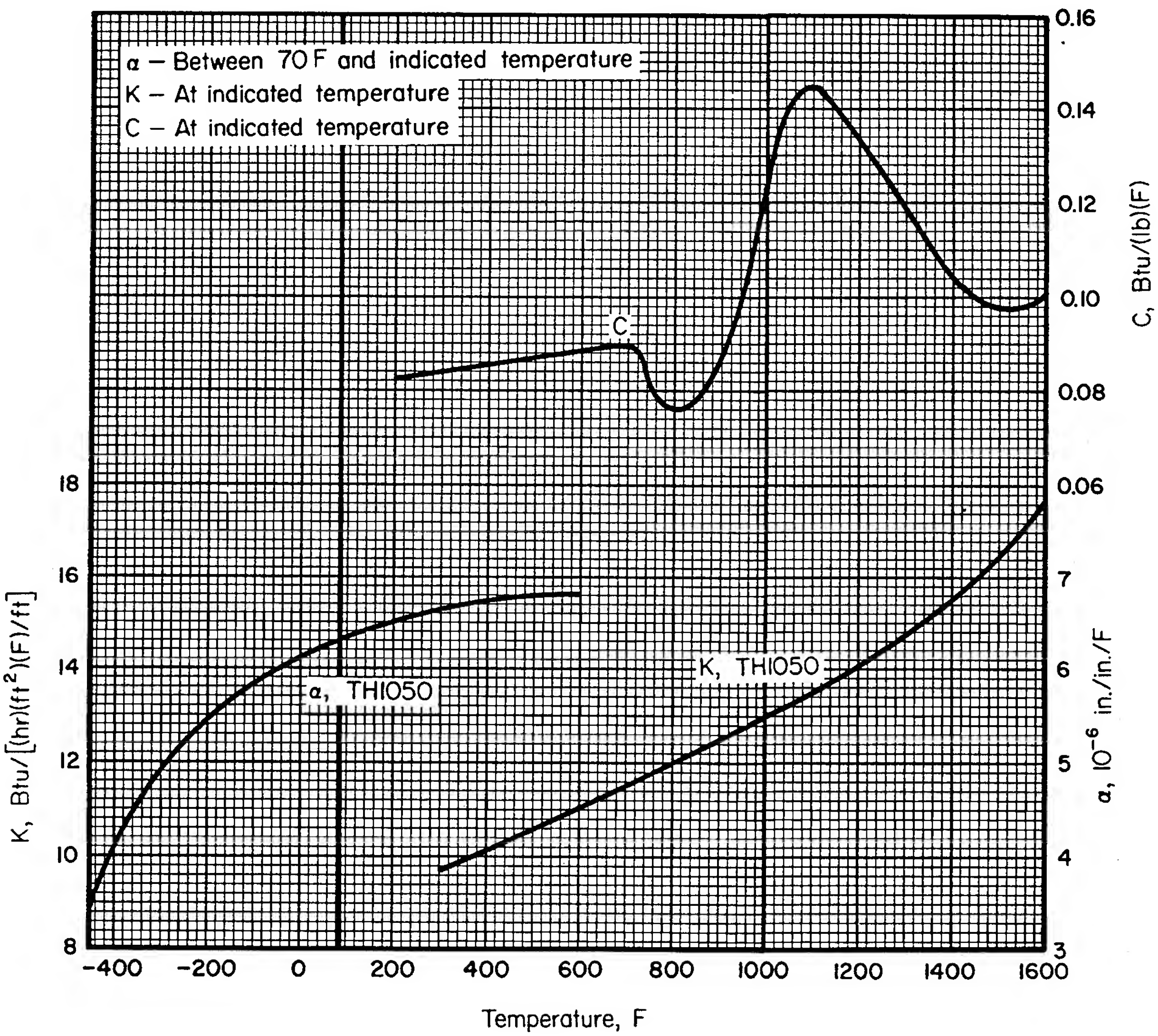

FIGURE 2.6.9.0. *Effect of temperature on the physical properties of 17-7PH stainless steel.*

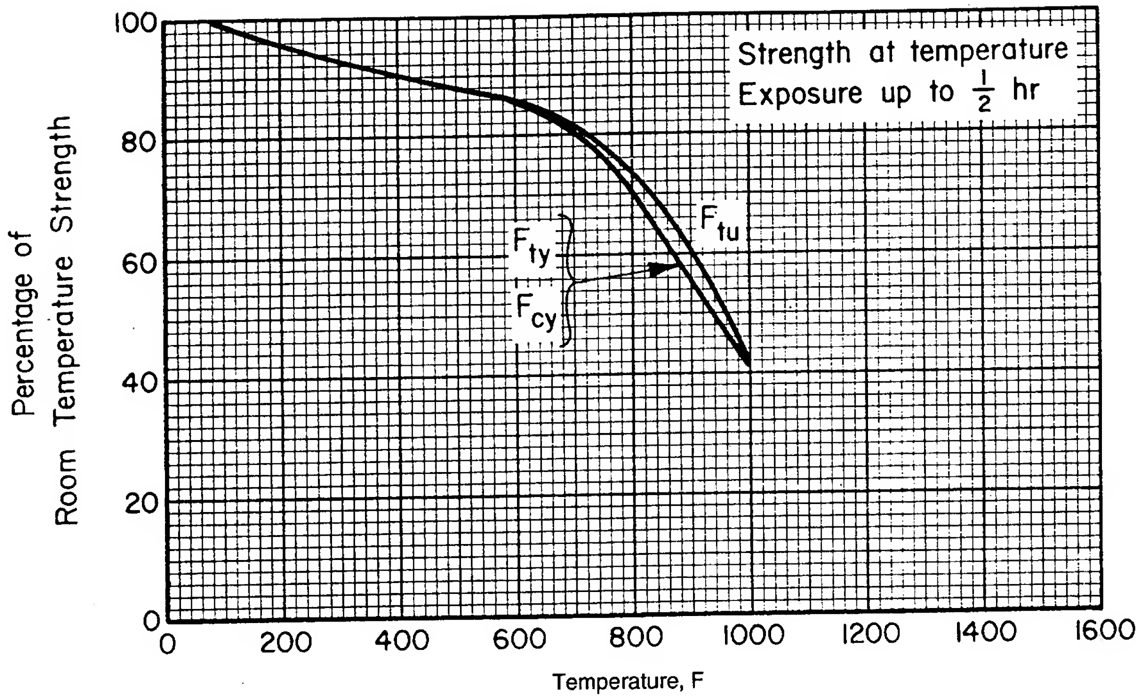

FIGURE 2.6.9.1.1. *Effect of temperature on the ultimate tensile strength (F_{to}), tensile yield strength (F_{ty}), and compressive yield strength (F_{cy}) of 17-7PH (TH1050) stainless steel sheet.*

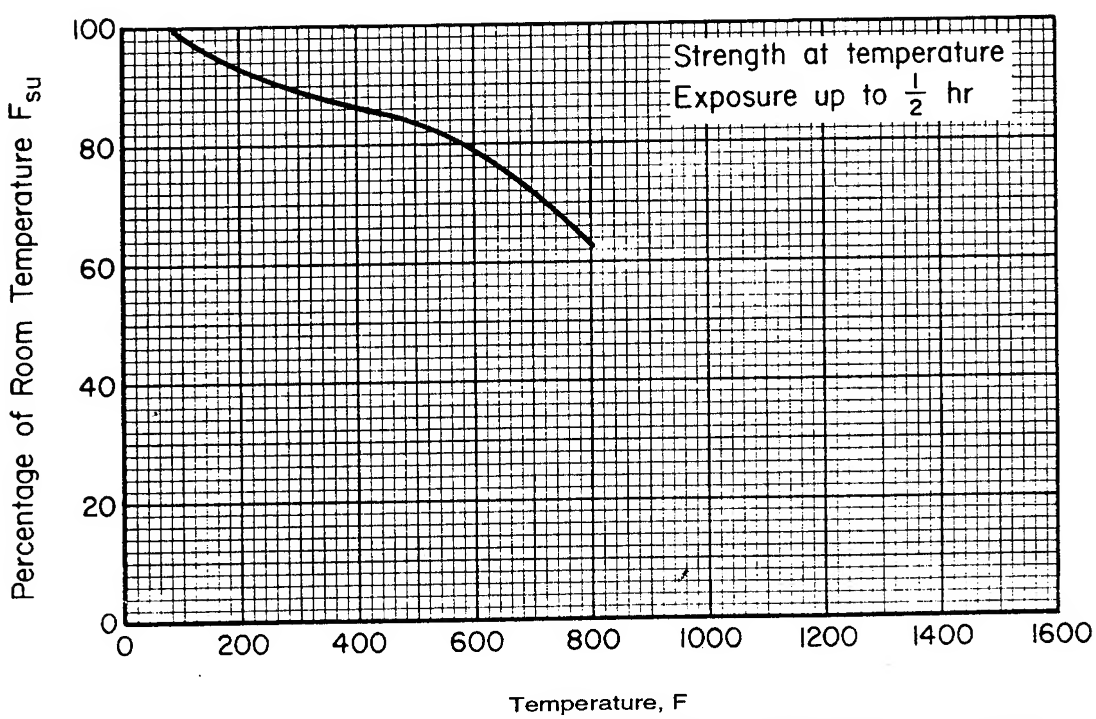

FIGURE 2.6.9.1.2. *Effect of temperature on the ultimate shear strength (F_{su}) of 17-7PH (TH1050) stainless steel sheet.*

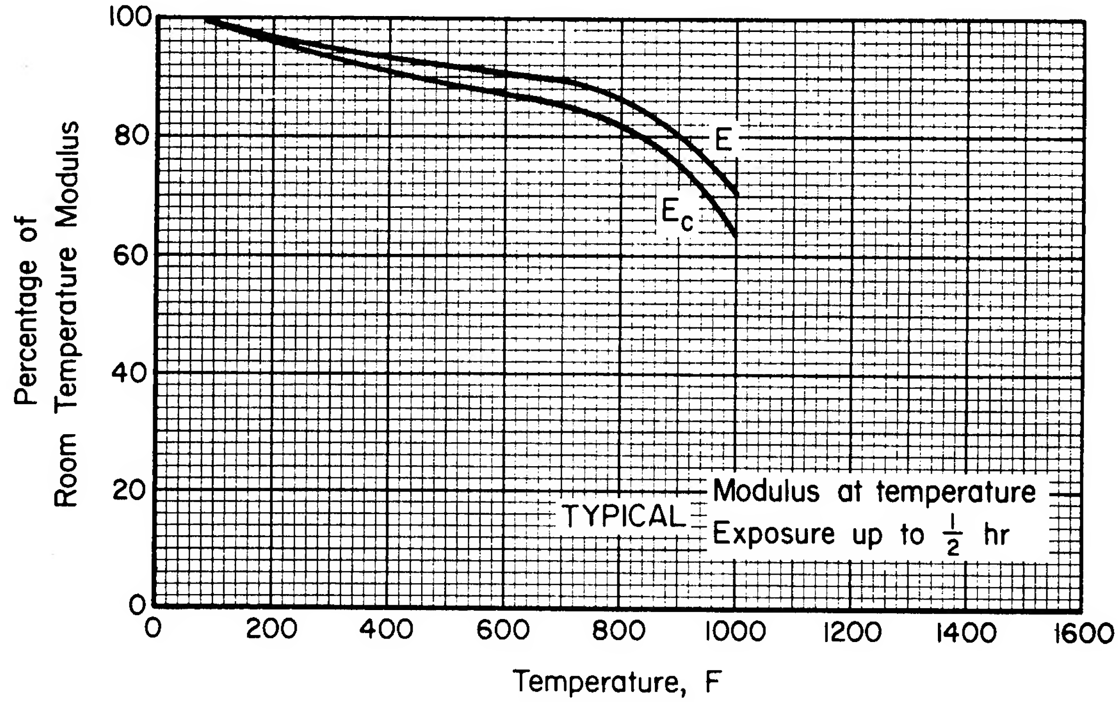

FIGURE 2.6.9.1.4(a). *Effect of temperature on the tensile and compressive moduli (E and E_c) of 17-7PH (TH1050) stainless steel sheet.*

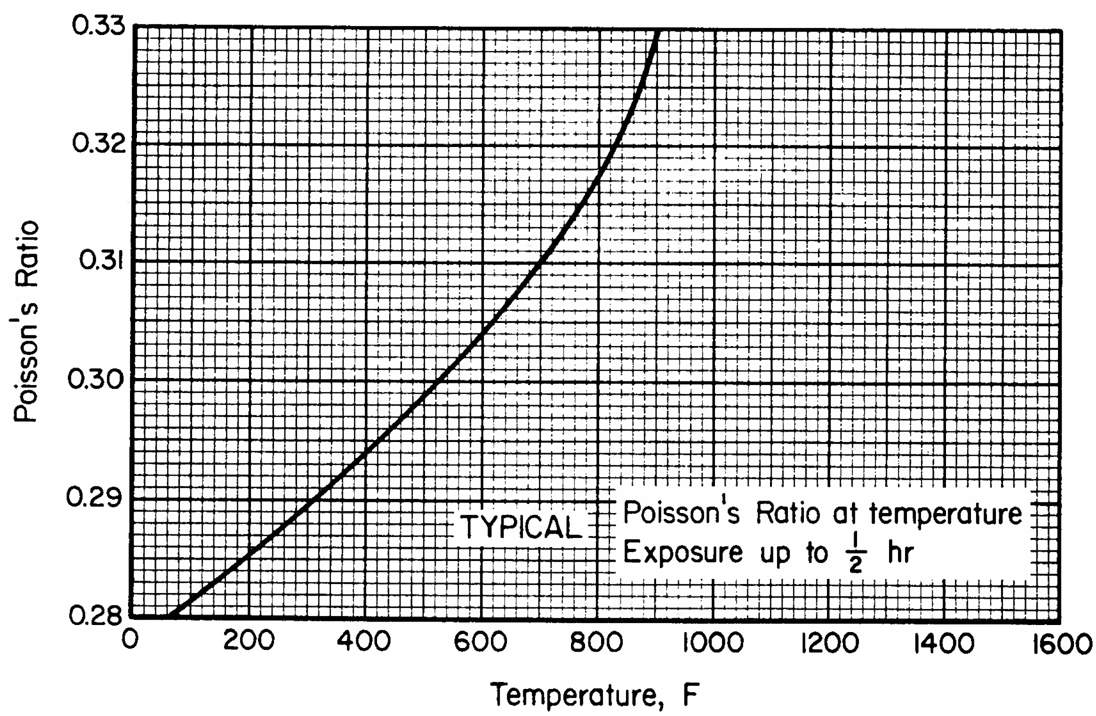

FIGURE 2.6.9.1.4(b). *Effect of temperature on Poisson's ratio (μ) for 17-7PH (TH1050) stainless steel sheet.*

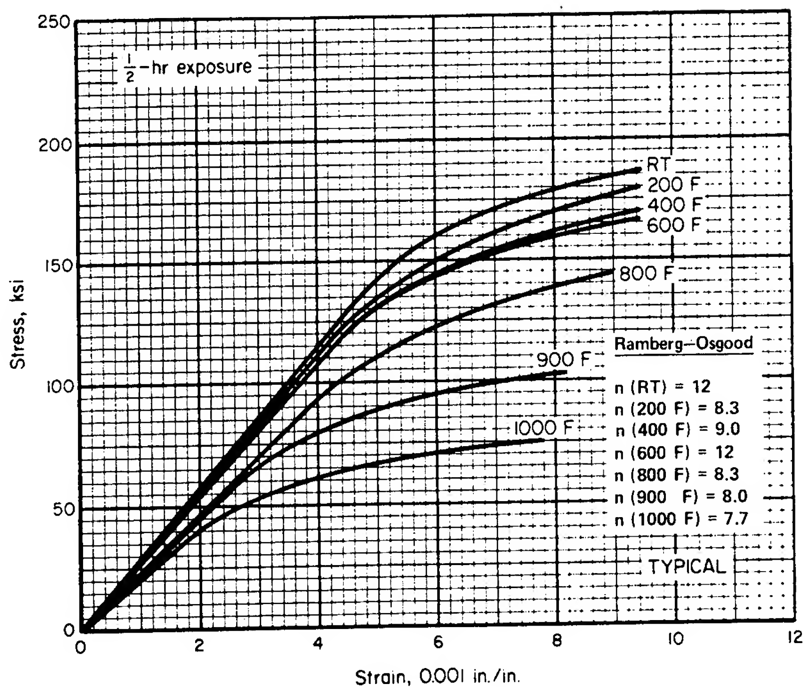

FIGURE 2.6.9.1.6(a). *Typical tensile stress-strain curves at various temperatures for 17-7PH (TH1050) stainless steel sheet.*

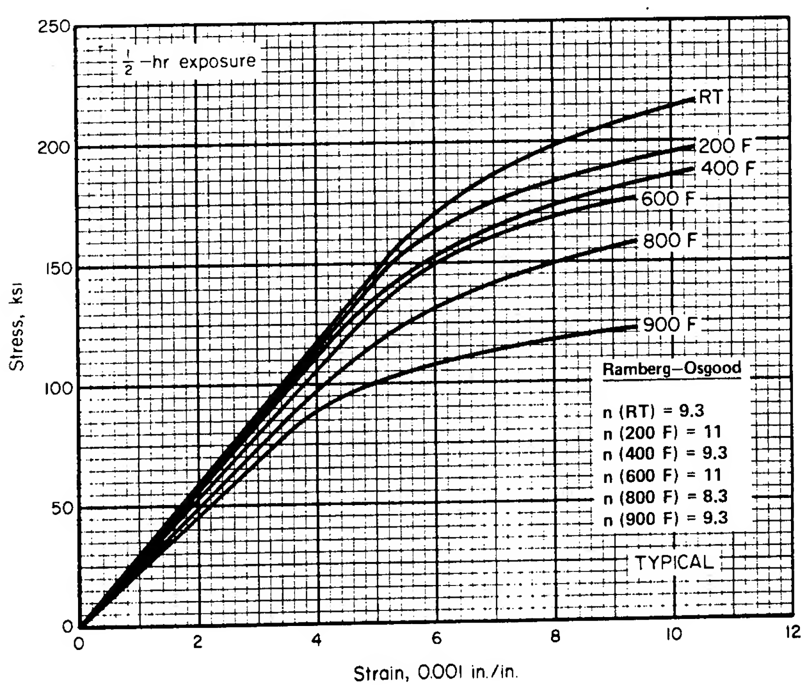

FIGURE 2.6.9.1.6(b). *Typical compressive stress-strain curves at various temperatures for 17-7PH (TH1050) stainless steel sheet.*

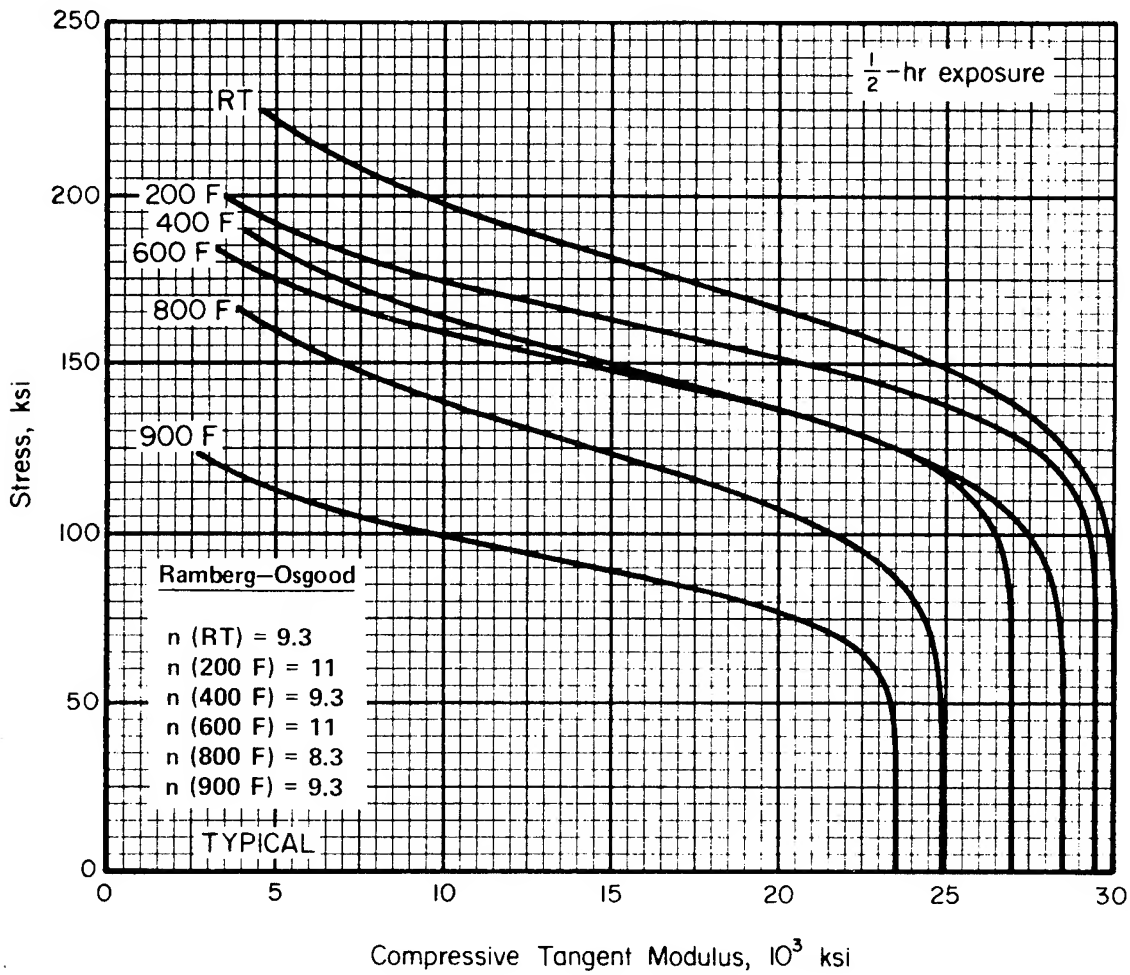

FIGURE 2.6.9.1.6(c). *Typical compressive tangent-modulus curves at various temperatures for 17-7PH (TH1050) stainless steel sheet.*

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2.7 Austenitic Stainless Steels

2.7.0 COMMENTS ON AUSTENITIC STAINLESS STEEL

2.7.0.1 *Metallurgical Considerations*.—The austenitic ("18-8") stainless steels were developed as corrosion-resistant alloys. However, they possess excellent oxidation resistance and good creep strength at elevated temperatures, along with good cold formability and other properties in airframe and missile applications. They are used in sheet form for portions of the airframe having ambient temperatures too high for aluminum alloys and, with the development of sandwich structures, are gaining additional uses. These steels are also used extensively at cryogenic temperatures.

The two alloying elements in the austenitic stainless steels are chromium and nickel. Chromium adds corrosion and oxidation resistance and high-temperature strength, and nickel gives an austenitic structure, with its associated toughness and ductility. The AISI 300 series stainless steels constitute a wide variety of compositions designed for different applications. The basic grade, Type 302, contains 18 percent chromium and 8 percent nickel. Varying one or both of these elements creates special characteristics. Type 301 (17 percent chromium and 7 percent nickel) work hardens to very high strengths. Type 310 (25 percent chromium and 20 percent nickel) has higher elevated temperature strength and greater oxidation resistance than Type 302. Sulfur and selenium additions promote free machining. Low carbon and/or columbium or titanium additions minimize intergranular corrosion for elevated temperature applications and welded construction. The addition of molybdenum improves corrosion resistance in reducing environments and gives improved creep resistance over Type 302. The characteristics of some of the AISI 300 series stainless steels are presented in Table 2.7.0.1.

These alloys are not hardenable by heat treatment but can achieve high strength levels through cold working. The strength imparted by cold working is decreased by exposure to temperatures above about 900 F.

2.7.0.2 *Manufacturing Considerations*

Forging.—The stainless steels have lower thermal conductivity than lower alloy steels and are susceptible to grain growth at forging temperatures. Hence, soaking times must be adequate to permit thorough heating of the billet but must be controlled carefully to limit grain growth when small reductions are involved during forging. At forging temperatures, the stainless steels are stronger than alloy steels, and forging must be conducted at higher temperatures and heavier forging equipment and more frequent reheating are required. The stainless steel billets forge much better when the surface is free of defects, and machine turning of the billets is advisable.

Cold Forming.—Because of their austenitic structure at room temperature, the stainless steels have excellent ductility for cold-forming operations when in the annealed condition. These steels work harden rapidly, and intermediate anneals may be required in deep drawing.

Machining.—The machining of the austenitic stainless steels is not difficult if proper steps are taken to combat the work-hardening tendencies of these steels. The use of heavy machines, slow speeds, deep cuts, and properly designed cutting tools with a fairly steep top rake produces the best results. Cold-worked material possesses somewhat better machinability than hot-finished, annealed material. These steels also are available in free-machining grades, containing sulfur or selenium.

Welding.—The austenitic stainless steels can be welded by almost any usual technique except carbon arc, provided adequate steps are taken to prevent oxidation or carburization of the weldment. The stabilized grades are preferred for welded parts that are used in the as-welded condition under corrosive conditions. The free-machining grades are not recommended for welding. Filler rods should be the same composition, or slightly higher in alloy content, as the material to be welded. Special fluxes designed for use with stainless steels should be employed, except in atomic hydrogen or inert-gas-shielded arc welding. Spot and roll seam welding also are used to a considerable extent.

TABLE 2.7.0.1. *Characteristics of Some AISI 300 Series Stainless Steels*

AISI	Characteristics
301	High work-hardening rate; applications requiring high strength and ductility.
302	Higher carbon modification of Type 304 for higher strength on cold rolling.
303	Free machining sulfur modification of Type 302.
303Se	Free machining selenium modification of Type 302.
304	General purpose austenitic grade for enhanced corrosion resistance.
304L	Low-carbon modification of Type 304 for welding applications.
305	Low work-hardening rate; spin forming and severe spin drawing operations.
309	High-temperature strength and oxidation resistance.
309S	Low-carbon modification of Type 309 for welded construction.
310	High-temperature strength and oxidation resistance greater than Type 309.
310S	Low-carbon modification of Type 310 for welded construction.
314	Increased oxidation resistance over Type 310.
316	Mo added to improve corrosion resistance in reducing environments; improved creep resistance over Type 302.
316L	Low-carbon modification of Type 316 for welded construction.
317	Increased Mo to improve corrosion resistance over Type 316 in reducing media.
321	Titanium stabilized for service in 800 to 1600 F range and to minimize carbide precipitation when welding for resistance to intergranular corrosion.
347	Columbium stabilized for service in 800 to 1600 F range and to minimize carbide precipitation when welding for resistance to intergranular corrosion.

Brazing.—Special techniques have been developed for silver-soldering and brazing these steels. Solders and fluxes especially designed should be used, surfaces must be thoroughly cleaned, and close control of temperature must be followed.

2.7.0.3 *Environmental Considerations.*—The austenitic stainless steels have excellent oxidation resistance at high temperatures, and their elevated-temperature service is usually limited by strength criteria. They also possess unusually good resistance to corrosion by most media. Prolonged exposure of the nonstabilized grades to temperatures between 700 and 1650 F makes them susceptible to intergranular corrosion.

2.7.1 AISI 301

2.7.1.0 *Comments and Properties.*—Of the austenitic stainless steels, AISI 301 is the one most frequently used at high strength levels in aircraft, mainly because of its greater work-hardening characteristics.

Type 301 is strengthened by cold working. If cold-worked Type 301 is subjected to temperatures above 900 F, its room-temperature strength is reduced.

Type 301 should not be used for extended periods at temperatures of 750 to 1650 F and should not be cooled slowly from higher temperatures through this range.

Material specifications for AISI 301 stainless steel are presented in Table 2.7.1.0(a). The room-temperature mechanical and physical properties for AISI 301 stainless steel are presented in Tables 2.7.1.0(b) and (c). The physical properties of this alloy at room and elevated temperatures are presented in Figure 2.7.1.0.

TABLE 2.7.1.0(a). *Material Specifications for AISI 301 Stainless Steel*

Specification	Form
MIL-S-5059	Plate, sheet, and strip
AMS 5517	Sheet and strip
AMS 5518	Sheet and strip
AMS 5519	Sheet and strip

2.7.1.1 *Annealed Condition.*—Elevated temperature curves for tensile yield and ultimate strengths are presented in Figures 2.7.1.1.1(a) and (b).

2.7.1.2 *¼ Hard Condition.*—Typical room-temperature stress-strain and tangent-modulus curves are presented in Figures 2.7.1.2.6(a) and (b).

2.7.1.3 *½ Hard Condition.*—Elevated temperature curves for various mechanical properties are presented in Figures 2.7.1.3.1 through 2.7.1.3.4. Typical stress-strain and tangent-modulus curves are presented in Figures 2.7.1.3.6(a) and (b).

2.7.1.4 *¾ Hard Condition.*—Typical room-temperature stress-strain and tangent-modulus curves are presented in Figures 2.7.1.4.6(a) and (b).

2.7.1.5 *Full-Hard Condition.*—The full-hard condition is a standard AISI temper and is developed by cold rolling 40 to 50 percent. Elevated temperature curves for various mechanical properties are presented in Figure 2.7.1.5.1 through 2.7.1.5.4. Tensile and compressive stress-strain as well as tangent-modulus curves at room temperature and several elevated temperatures are presented in Figures 2.7.1.5.6(a) through (d).

TABLE 2.7.1.0(b). *Design Mechanical and Physical Properties of AISI 301 and Other[a] Annealed Stainless Steel*

Specification	MIL-S-5059	AMS 5517 & MIL-S-5059		AMS 5518 & MIL-S-5059		MIL-S-5059		AMS 5519 & MIL-S-5059	
Form	Sheet and strip								
Condition	Annealed[a]	¼ Hard		½ Hard		¾ Hard		Full Hard	
Thickness, in.	≤0.187	...		...		...		...	
Basis	S	A	B	A	B	A	B	A	B
Mechanical Properties:									
F_{tu}, ksi:									
L	73	124	129	141	151	157	168	174	185
LT	75	122	127	142	152	163	173	175	186
F_{ty}, ksi:									
L	26	69	83	93	110	118	135	137	153
LT	30	67	82	92	105	113	133	125	142
F_{cy}, ksi:									
L	23	44	54	61	69	75	88	83	94
LT	29	71	88	100	116	127	152	142	164
F_{su}, ksi	50	66	69	77	82	88	93	95	100
F_{bru}, ksi:									
(e/D = 1.5)	...	...	...	...	...	...	...	...	...
(e/D = 2.0)	162	262	273	292	310	327	342	346	361
F_{bry}, ksi:									
(e/D = 1.5)	...	...	...	...	...	...	...	...	...
(e/D = 2.0)	55	123	149	167	189	202	234	222	249
e, percent (S basis):									
LT	40	25	...	b	...	b	...	b	...
E, 10^3 ksi:									
L	29.0	27.0		26.0		26.0		26.0	
LT	29.0	28.0		28.0		28.0		28.0	
E_c, 10^3 ksi:									
L	28.0	26.0		26.0		26.0		26.0	
LT	28.0	27.0		27.0		27.0		27.0	
G, 10^3 ksi	11.2	10.6		10.5		10.5		10.5	
μ	0.27	0.27		0.27		0.27		0.27	
Physical Properties:									
ω, lb/in.^{3}	0.286								
C, K, and α	See Figure 2.7.1.0								

[a]Properties for annealed (solution heat treated) condition also applicable to AISI 301 plate and to AISI 302, 303, 304, 321, and 347 sheet, strip, and plate, supplied to industry specifications.
[b]See Table 2.7.1.0(c).

Note: Yield strength, particularly in compression, and modulus of elasticity in the longitudinal direction may be raised appreciably by thermal stress-relieving treatment in the range 500 to 800 F.

TABLE 2.7.1.0(c). *Minimum Elongation Values for AISI 301 Stainless Steel Sheet and Strip*

Condition	Thickness, inches	Elongation (LT), percent
½ hard	0.015 and under	15
	0.016 and over	18
¾ hard	0.015 and under	10
	0.016 and over	12
Full hard	0.015 and under	8
	0.016 and over	9

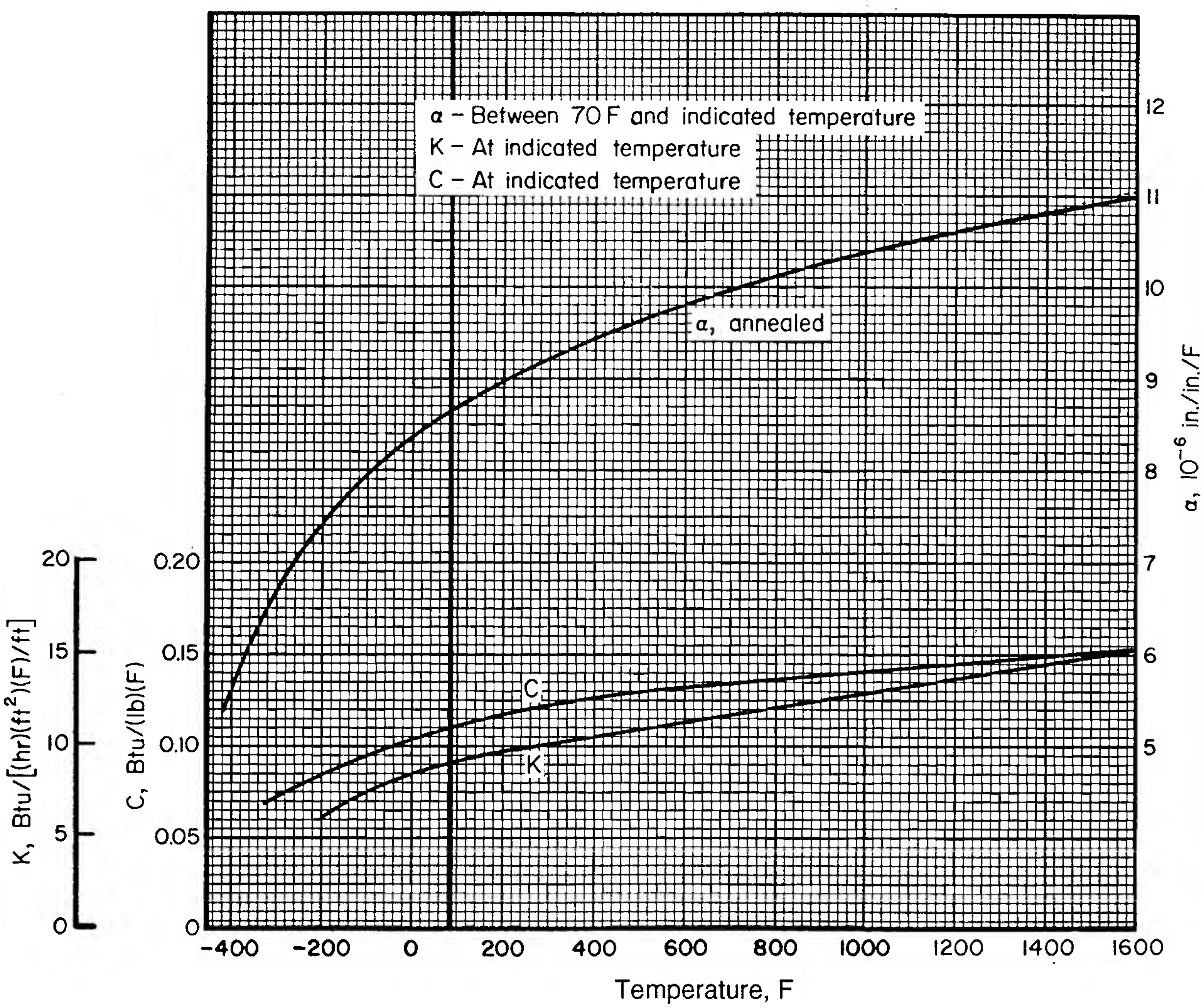

FIGURE 2.7.1.0. *Effect of temperature on the physical properties of AISI 301 stainless steel.*

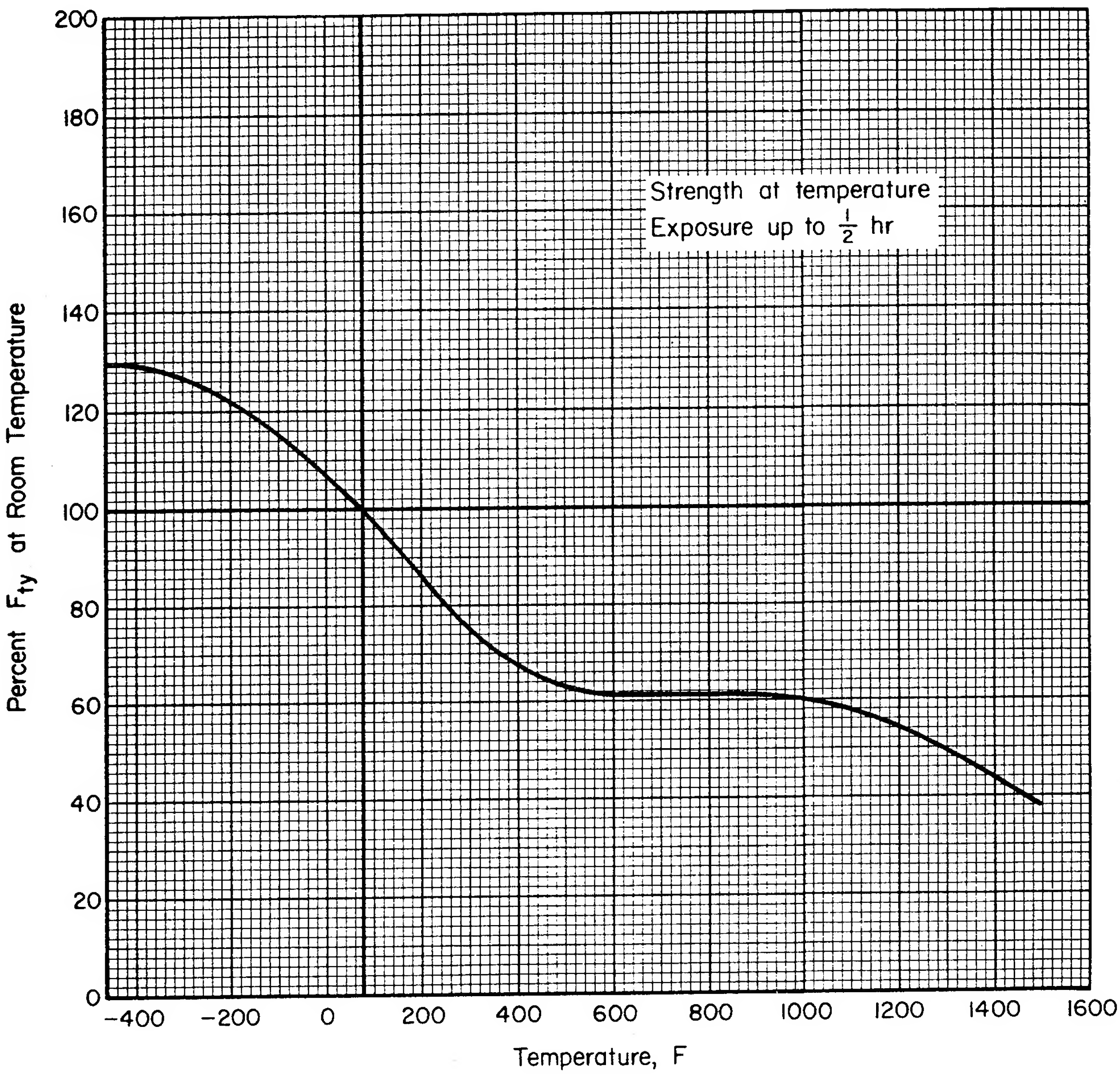

FIGURE 2.7.1.1.1.(a) *Effect of temperature on the tensile yield strength (F_{by}) if AISI 301, 302, 304, 304L, 321, and 347 annealed stainless steel.*

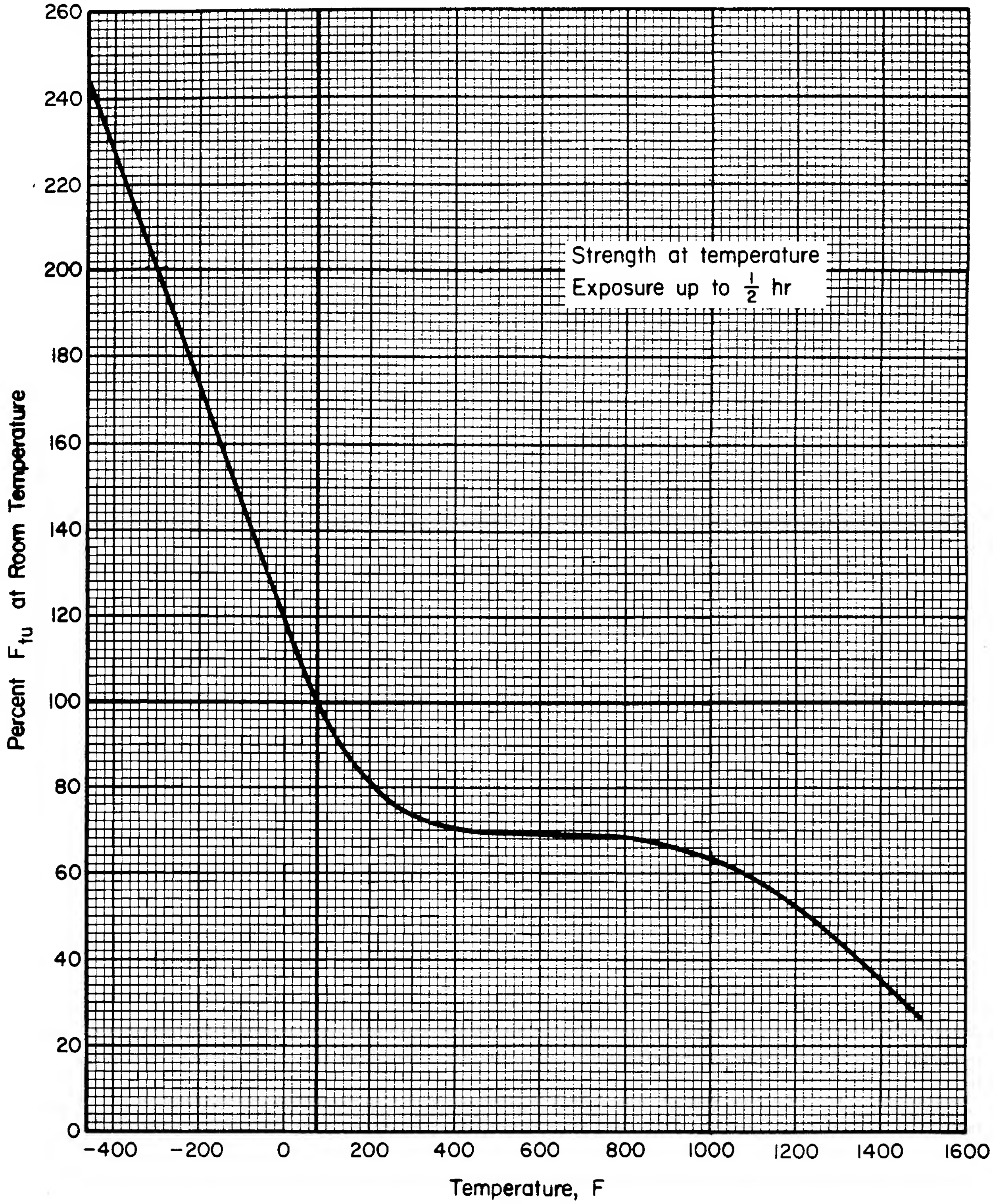

FIGURE 2.7.1.1.1(b). *Effect of temperature on the tensile ultimate strength (F_{tu}) of AISI 301, 302, 304, 304L, 321, and 347 annealed stainless steel.*

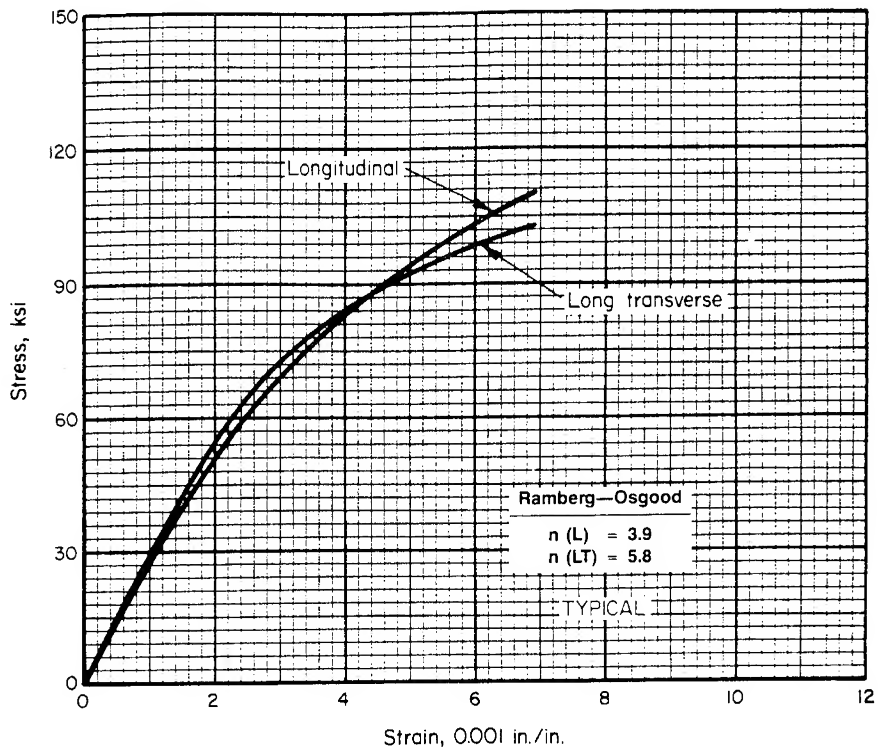

FIGURE 2.7.1.2.6(a). *Typical tensile stress-strain curves at room temperature for AISI 301 1/4-hard stainless steel sheet.*

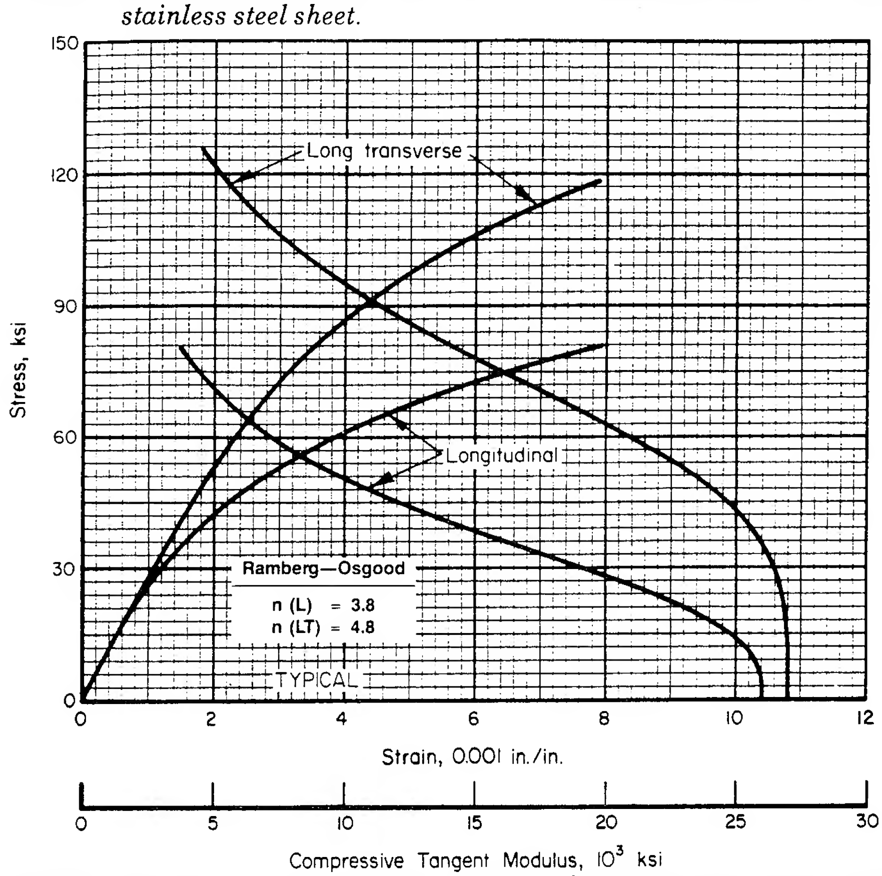

FIGURE 2.7.1.2.6(b). *Typical compressive stress-strain and compressive tangent-modulus curves at room temperature for AISI 301 1/4-hard stainless steel sheet.*

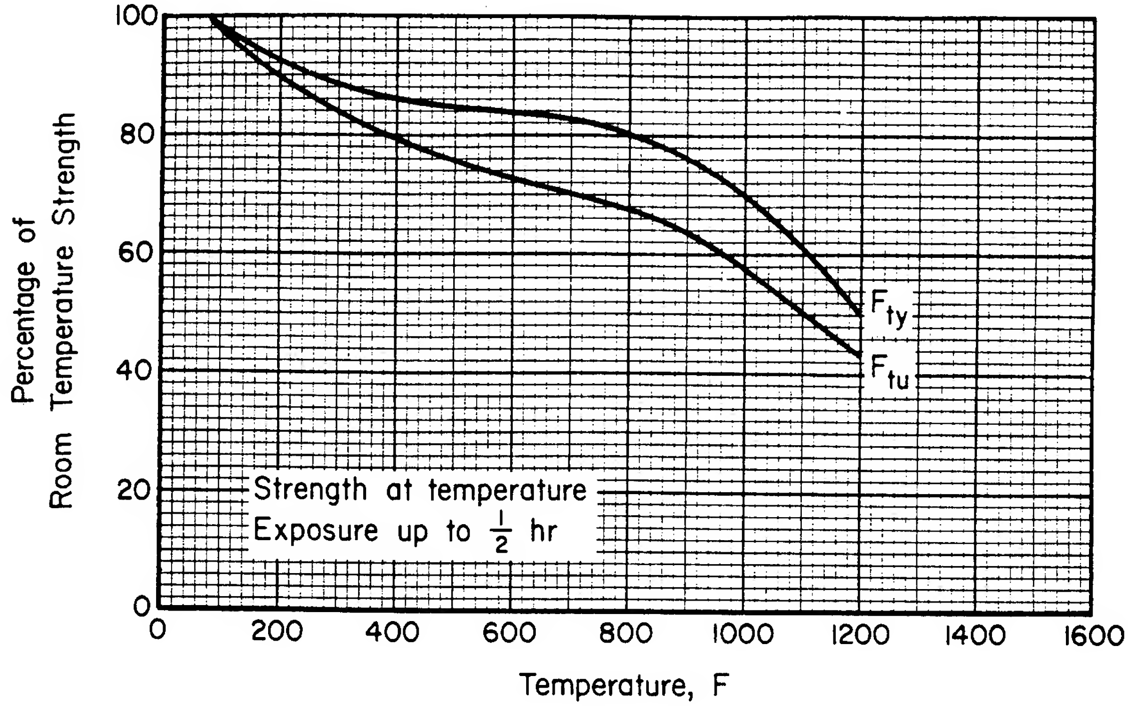

FIGURE 2.7.1.3.1. *Effect of temperature on the tensile ultimate strength (F_{tu}) and the tensile yield strength (F_{ty}) of AISI 301 1/2-hard stainless steel sheet.*

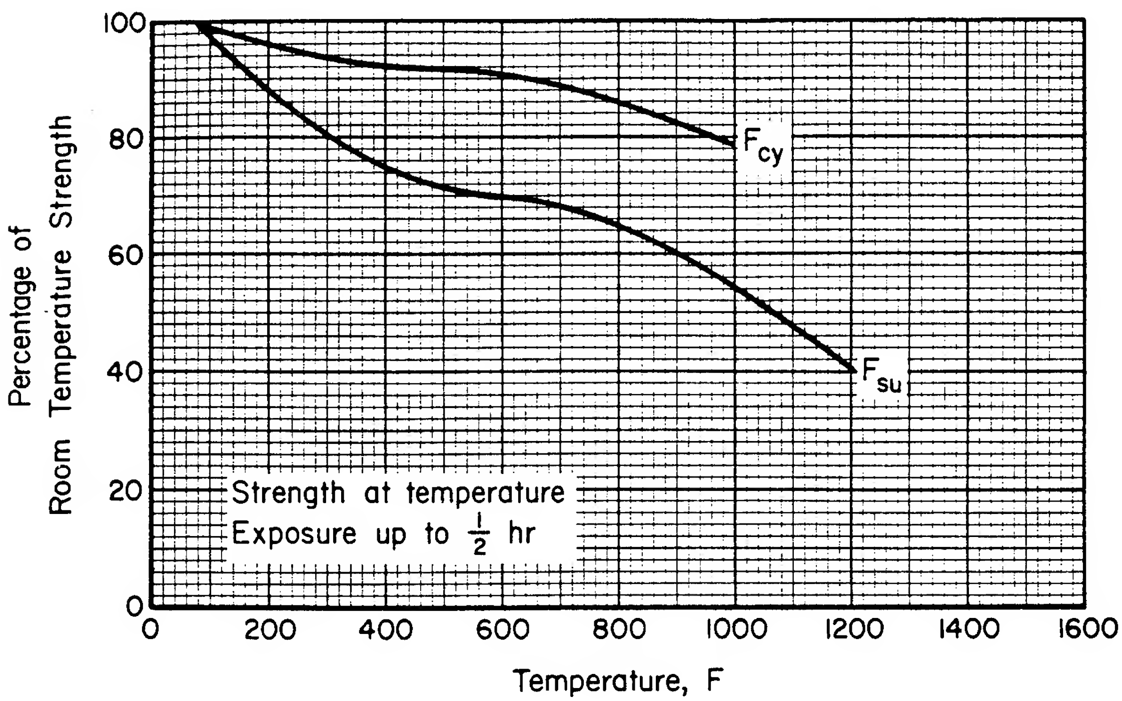

FIGURE 2.7.1.3.2. *Effect of temperature on the compressive yield strength (F_{cy}) and the shear ultimate strength (F_{su}) of AISI 301 1/2-hard stainless steel sheet.*

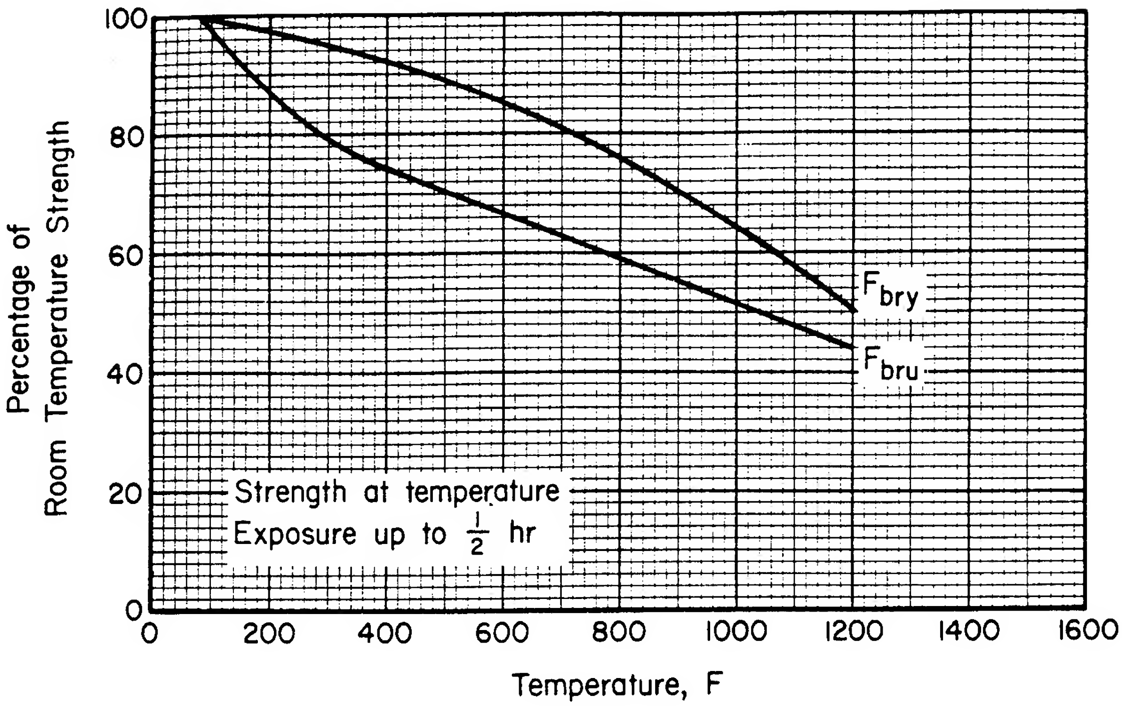

FIGURE 2.7.1.3.3. *Effect of temperature on the bearing ultimate strength (F_{bru}) and the bearing yield strength (F_{bry}) of AISI 301 1/2-hard stainless steel sheet.*

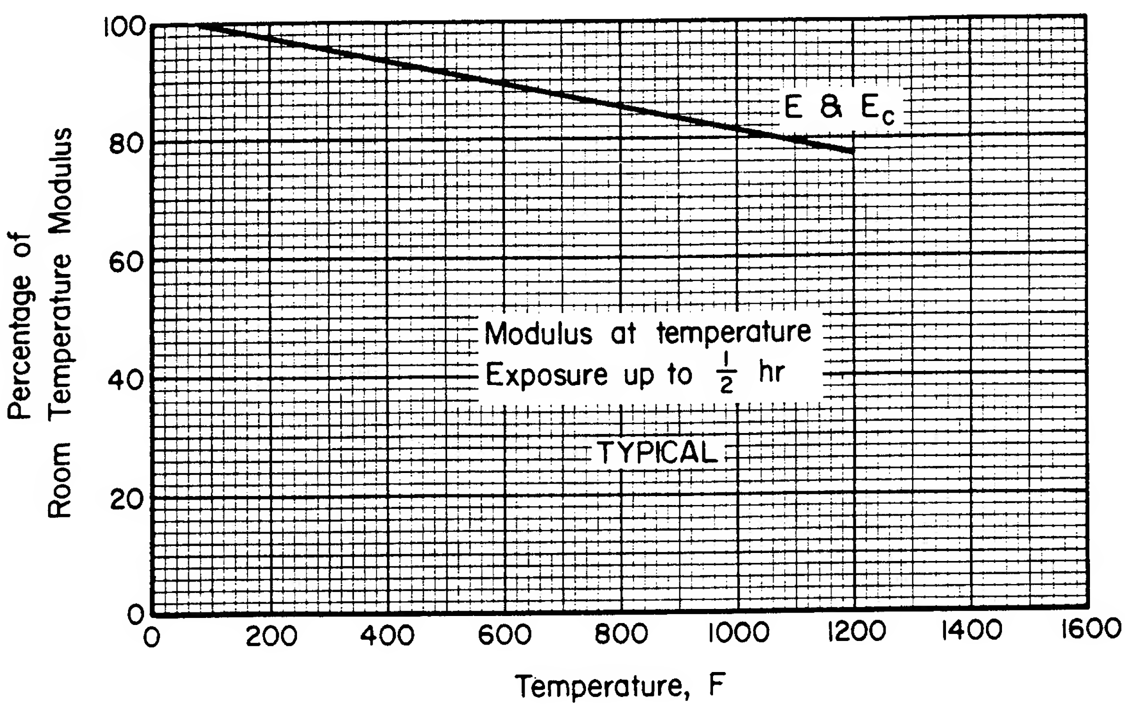

FIGURE 2.7.1.3.4. *Effect of temperature on the tensile and compressive moduli (E and E_c) of AISI 301 1/2-hard stainless steel sheet.*

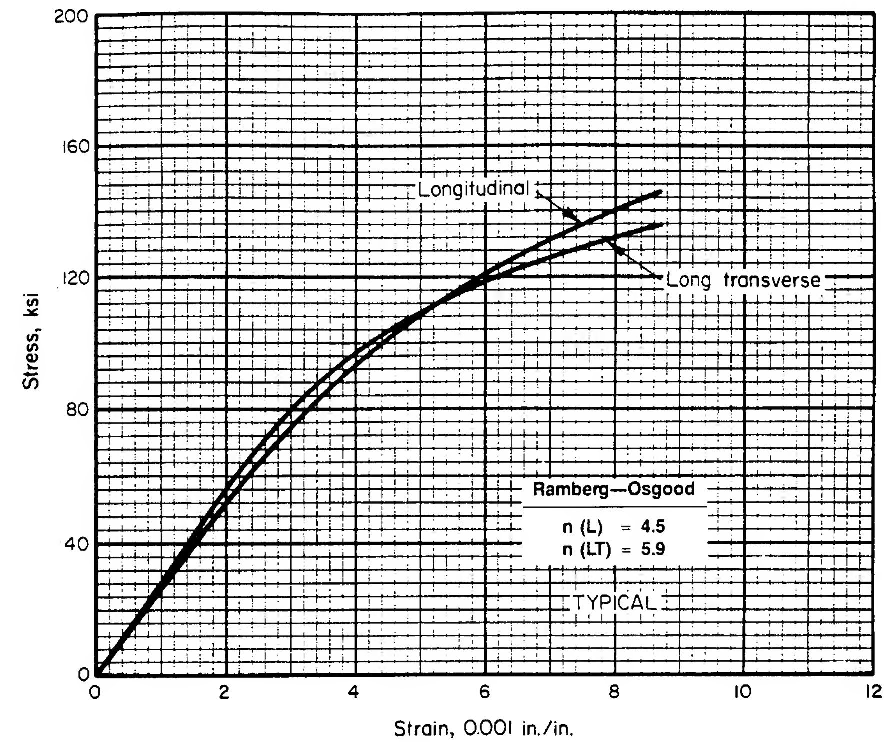

FIGURE 2.7.1.3.6(a). *Typical tensile stress-strain curves at room temperature for AISI 301 1/2-hard stainless steel sheet.*

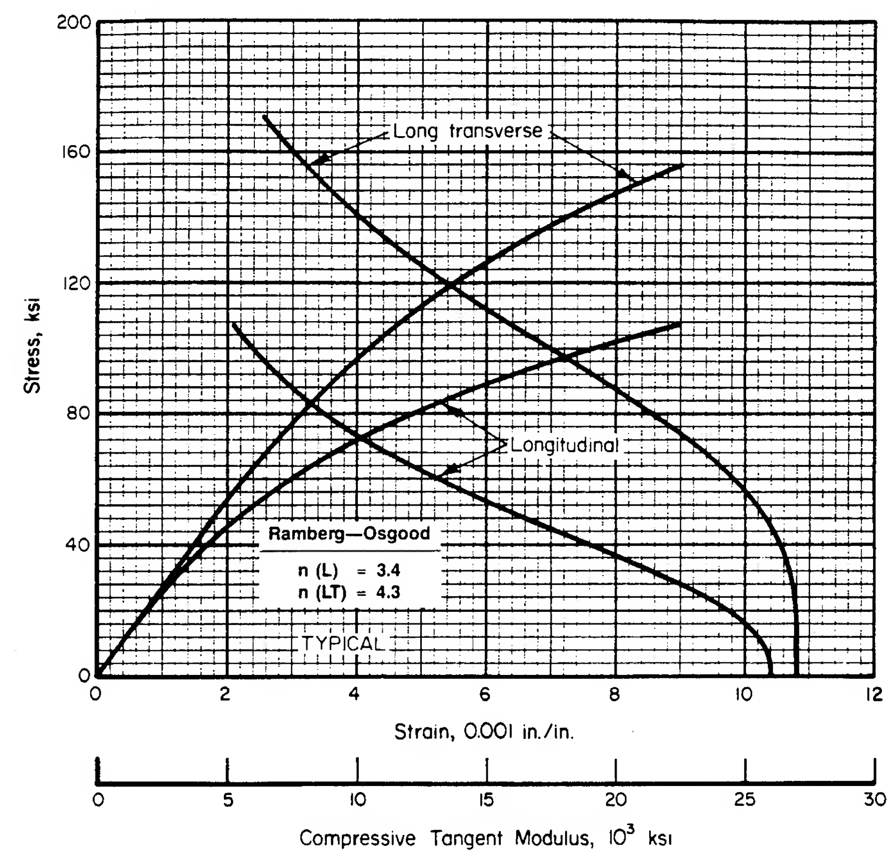

FIGURE 2.7.1.3.6(b). *Typical compressive stress-strain and compressive tangent-modulus curves at room temperature for AISI 301 1/2-hard stainless steel sheet.*

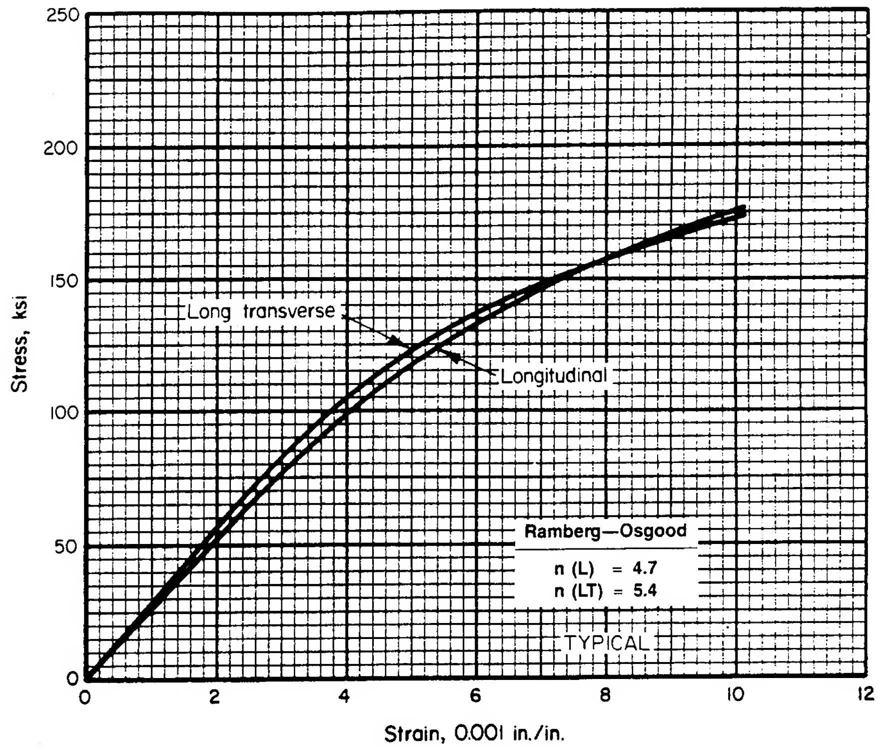

FIGURE 2.7.1.4.6(a). *Typical tensile stress-strain curves at room temperature for AISI 301 3/4-hard stainless steel sheet.*

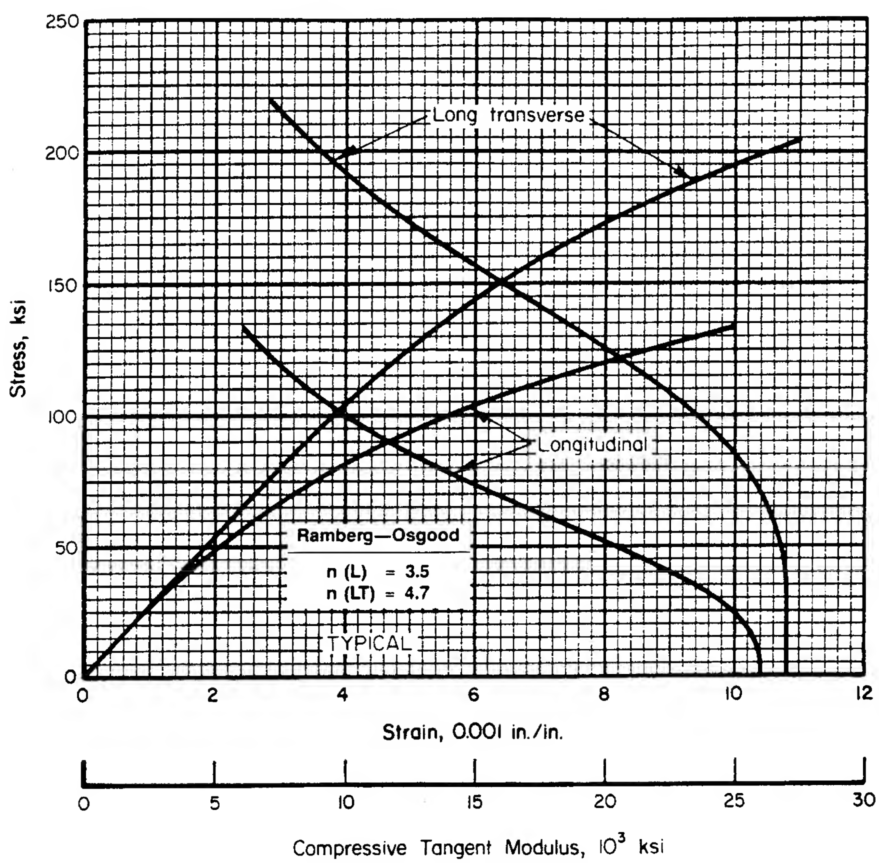

FIGURE 2.7.1.4.6(b). *Typical compressive stress-strain and compressive tangent-modulus curves at room temperature for AISI 301 3/4-hard stainless steel sheet.*

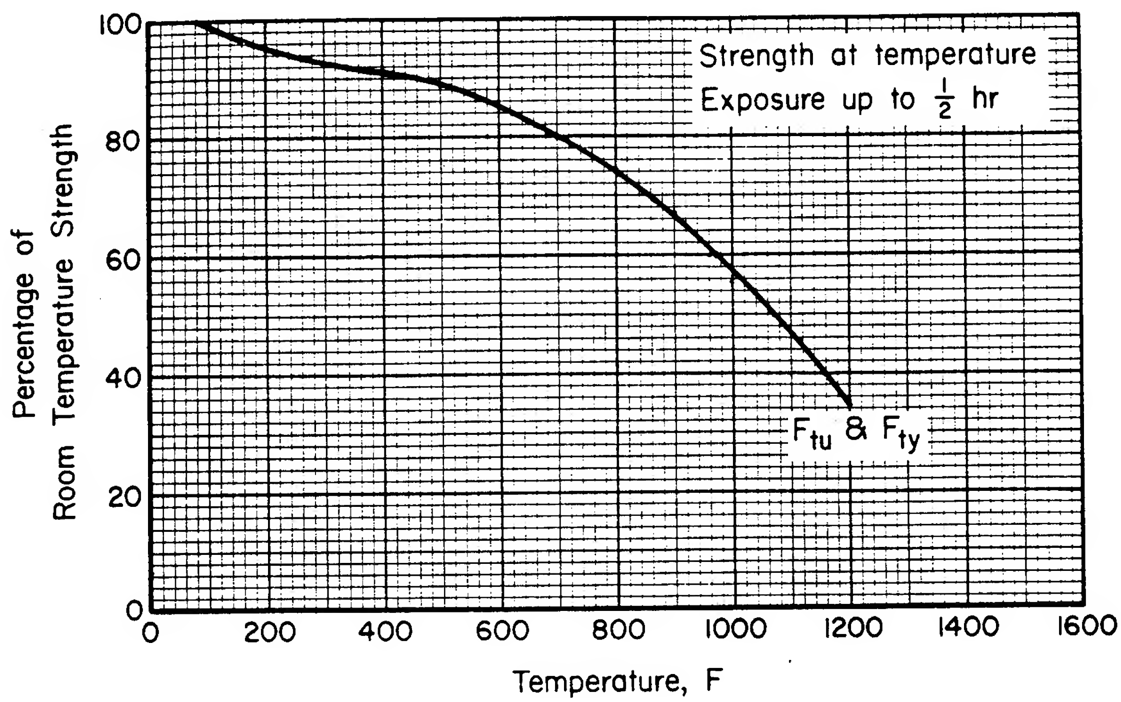

FIGURE 2.7.1.5.1. *Effect of temperature on the tensile ultimate strength (F_{tu}) and the tensile yield strength (F_{ty}) of AISI 301 full-hard stainless steel sheet.*

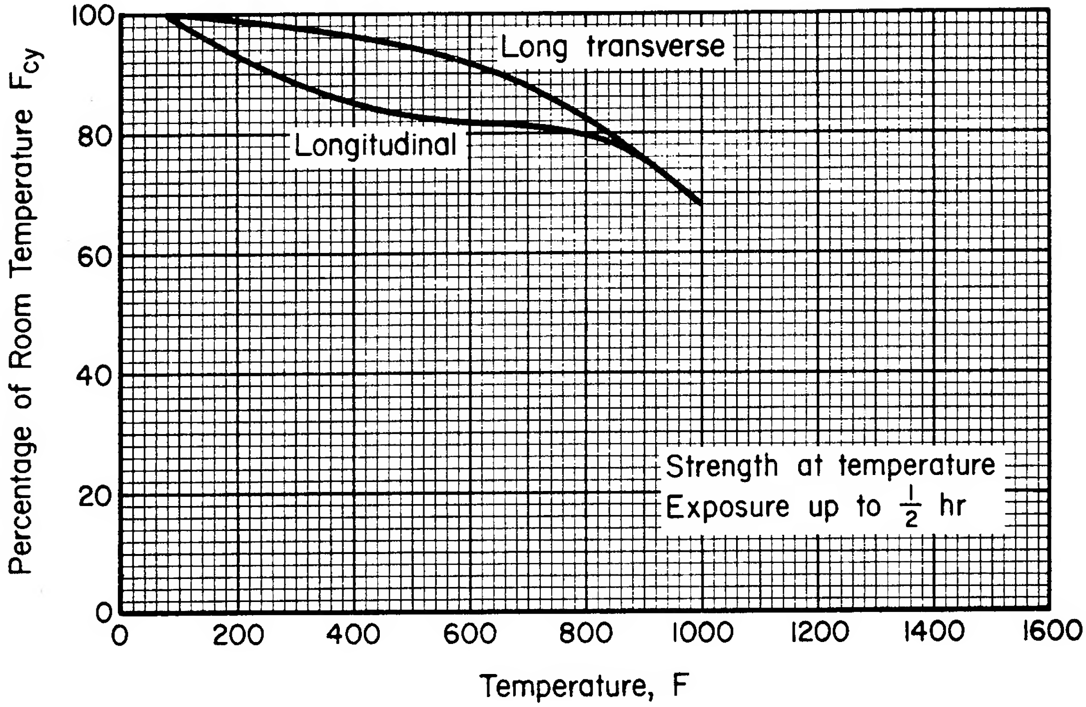

FIGURE 2.7.1.5.2(a). *Effect of temperature on the compressive yield strength (F_{cy}) of AISI 301 (full-hard) stainless steel sheet.*

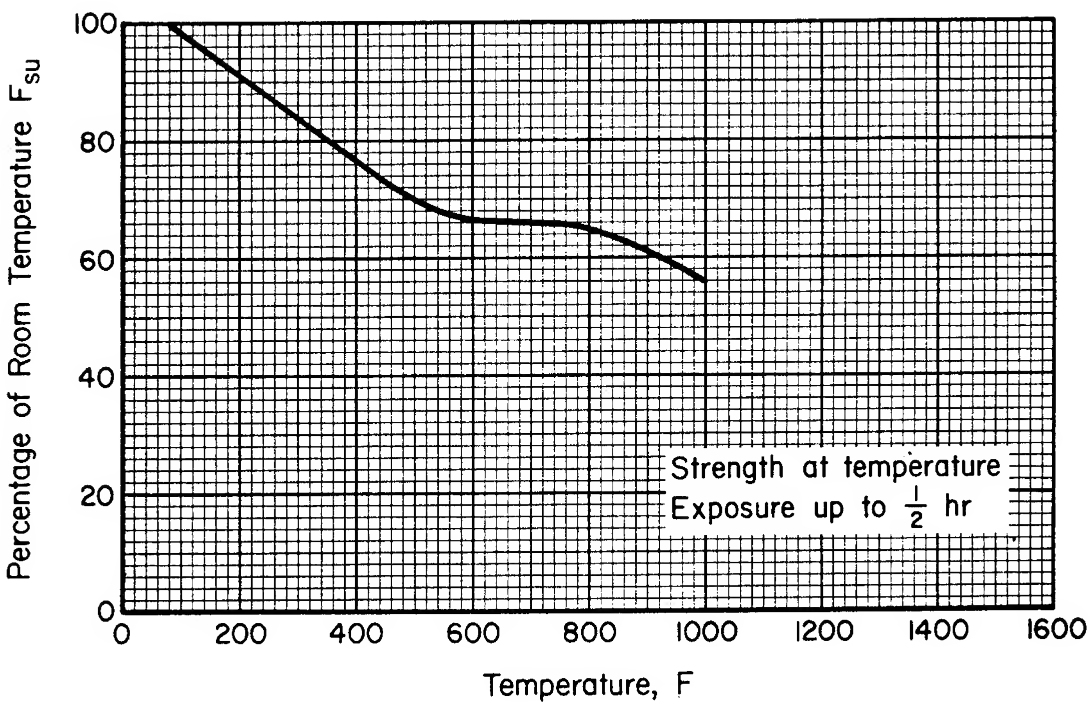

FIGURE 2.7.1.5.2(b). *Effect of temperature on the ultimate shear strength (F_{su}) of AISI 301 (full-hard) stainless steel sheet.*

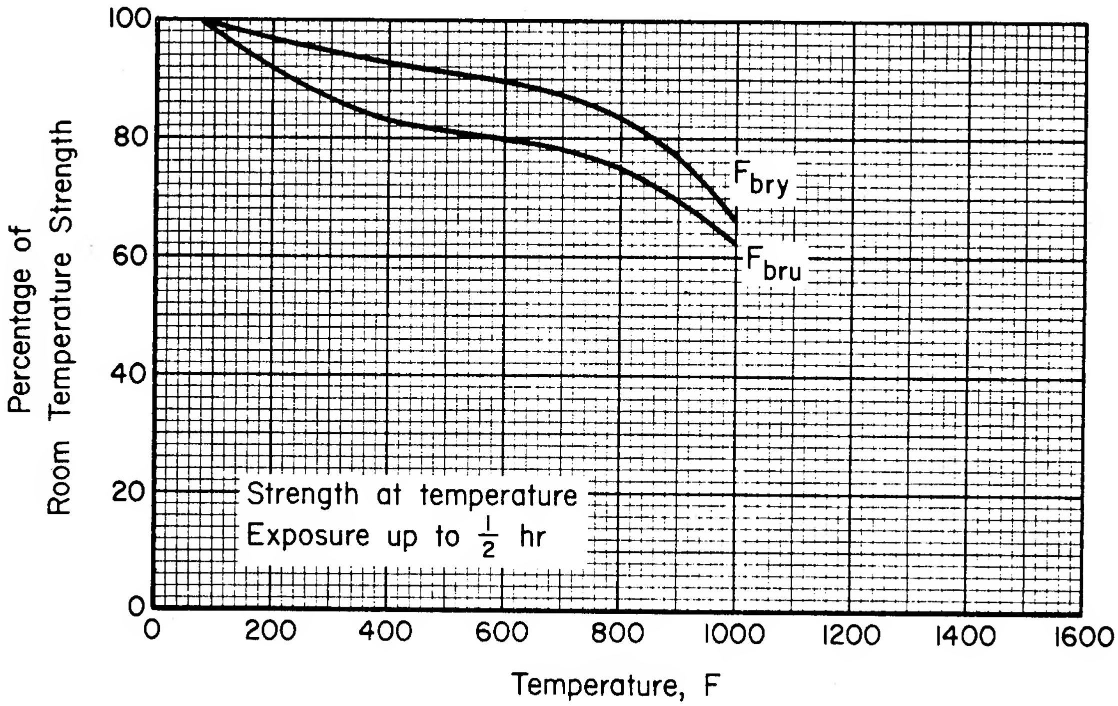

FIGURE 2.7.1.5.3. *Effect of temperature on the bearing ultimate strength (F_{bru}) and the bearing yield strength (F_{bry}) of AISI 301 (full-hard) stainless steel sheet.*

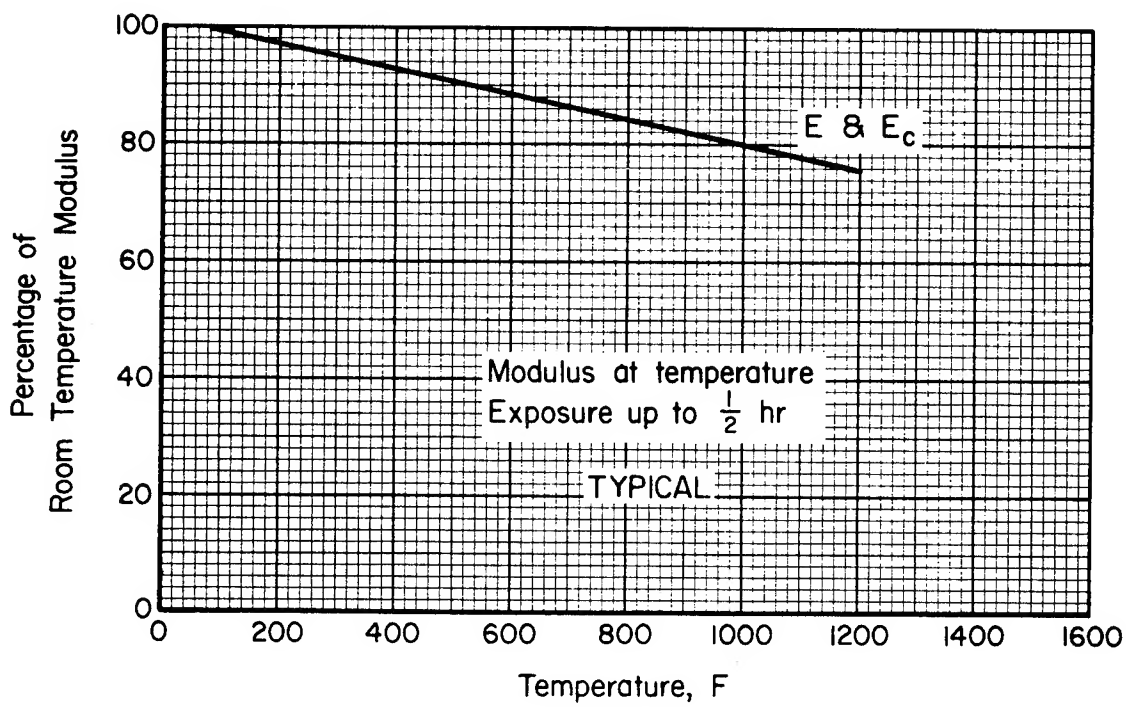

FIGURE 2.7.1.5.4. *Effect of temperature on the tensile and compressive moduli (E and E_c) of AISI 301 (full-hard) stainless steel sheet.*

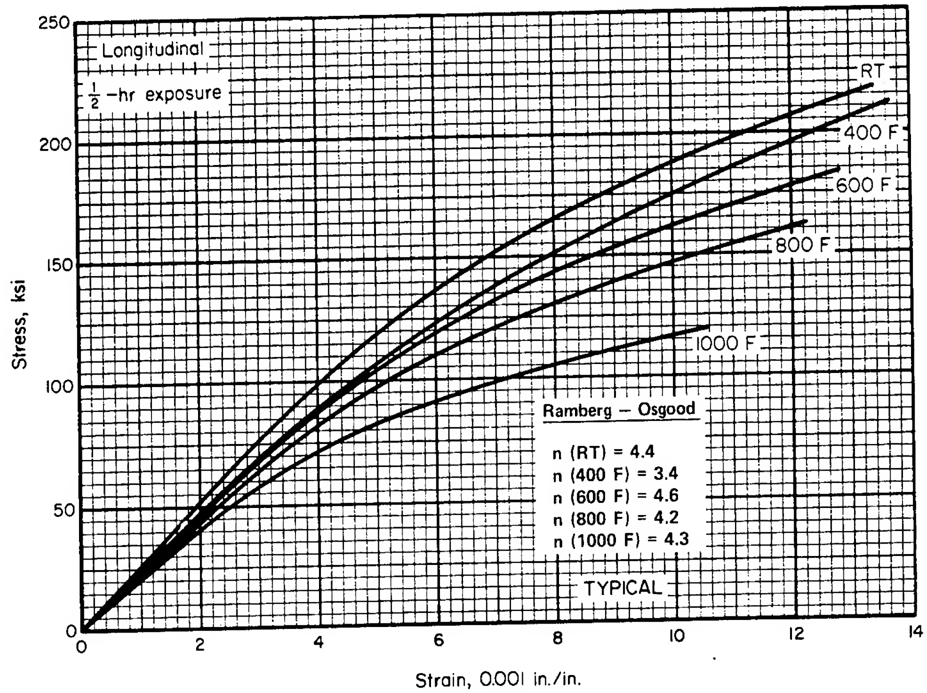

FIGURE 2.7.1.5.6(a). *Typical tensile stress-strain curves at room and elevated temperatures for AISI 301 (full-hard) stainless steel sheet.*

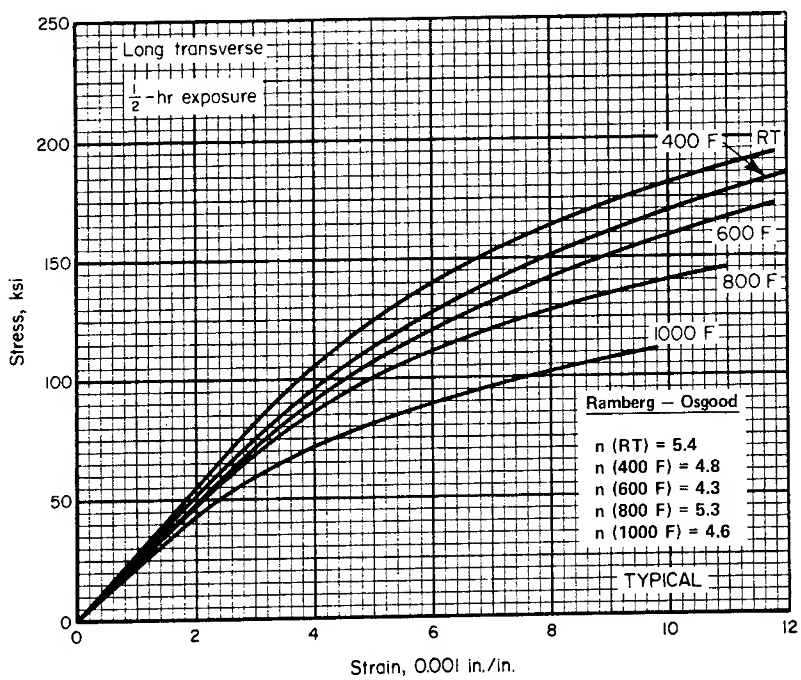

FIGURE 2.7.1.5.6(b). *Typical tensile stress-strain curves at room and elevated temperatures for AISI 301 (full-hard) stainless steel sheet.*

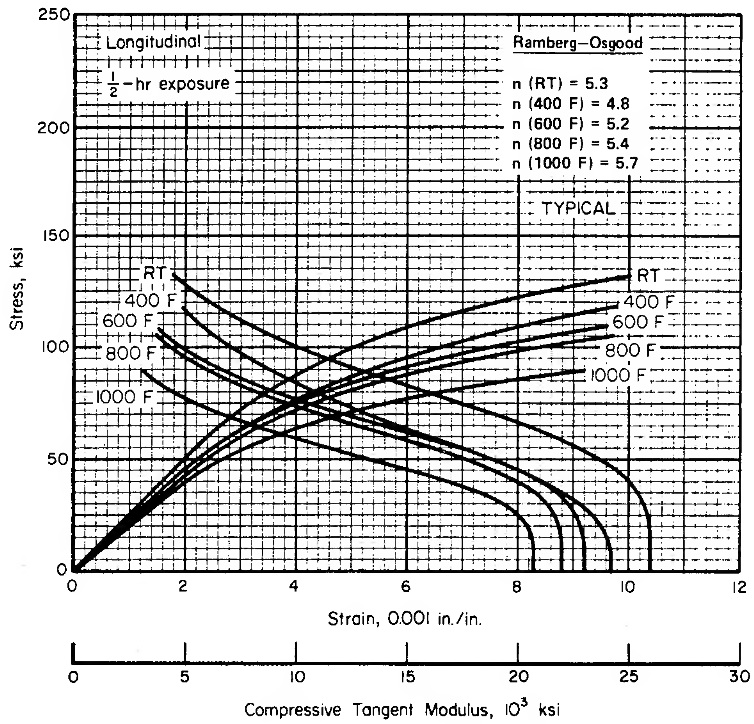

FIGURE 2.7.1.5.6(c). *Typical compressive stress-strain and compressive tangent-modulus curves at room and elevated temperatures for AISI 301 (full-hard) stainless steel sheet.*

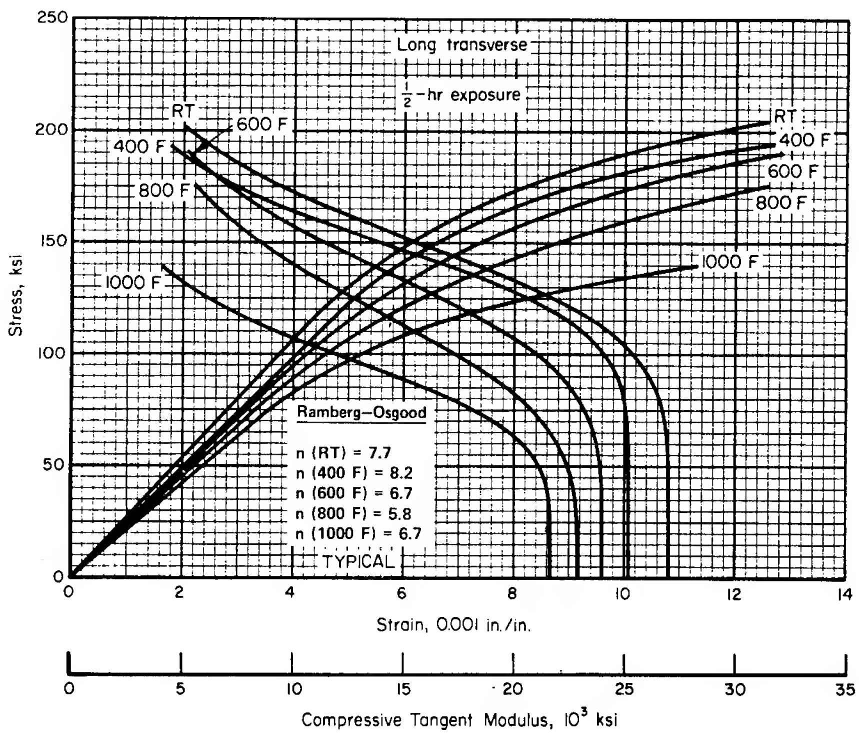

FIGURE 2.7.1.5.6(d). *Typical compressive stress-strain and compressive tangent-modulus curves at room and elevated temperatures for AISI 301 (full-hard) stainless steel sheet.*

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2.8 Element Properties

2.8.1 BEAMS.—See Equation 1.3.2.3, Section 1.5.2.5, and References 1.7.1(a) and (b) for general information on stress analysis of beams.

2.8.1.1 *Simple Beams.*—Beams of solid, tubular, or similar cross sections, not subject to instability (buckling, crippling, column, lateral bending) can be assumed to fail through exceeding an allowable modulus of rupture in bending, F_b, the value of which will depend upon beam cross-section geometry and beam material stress-strain characteristics. The modulus of rupture in bending is further discussed in Section 1.5.2.5. See Reference 2.8.1.1.

Round Tubes.—For round tubes, the value of F_b, will depend on the D/t ratio, as well as the ultimate tensile stress. Figure 2.8.1.1 gives the bending modulus of rupture for round alloy-steel tubing.

Unconventional Cross Sections.—Sections other than solid or tubular should be tested to determine the allowable bending stress.

2.8.1.2 *Built-Up Beams.*—Built-up beams usually fail because of local failures of the component parts. In welded steel tube beams, the allowable tensile stresses should be reduced properly for the effects of welding.

2.8.1.3 *Thin-Web Beams.*—The allowable stresses for thin-web beams will depend on the nature of the failure and are determined from the allowable stresses of the web in tension and of the flanges and stiffeners in compression.

2.8.2 COLUMNS

2.8.2.1 *General.*—The general formula for primary instability is given in Section 1.3.8. Both primary and local instability are discussed in Section 1.6.

2.8.2.2 *Effects of Welding.*—The primary failure stress of a column having welded ends can be determined from column curves or the column formula with the restriction that the column stress shall not exceed a "cut-off" stress which accounts for the effect of welding on the local failure of the column.

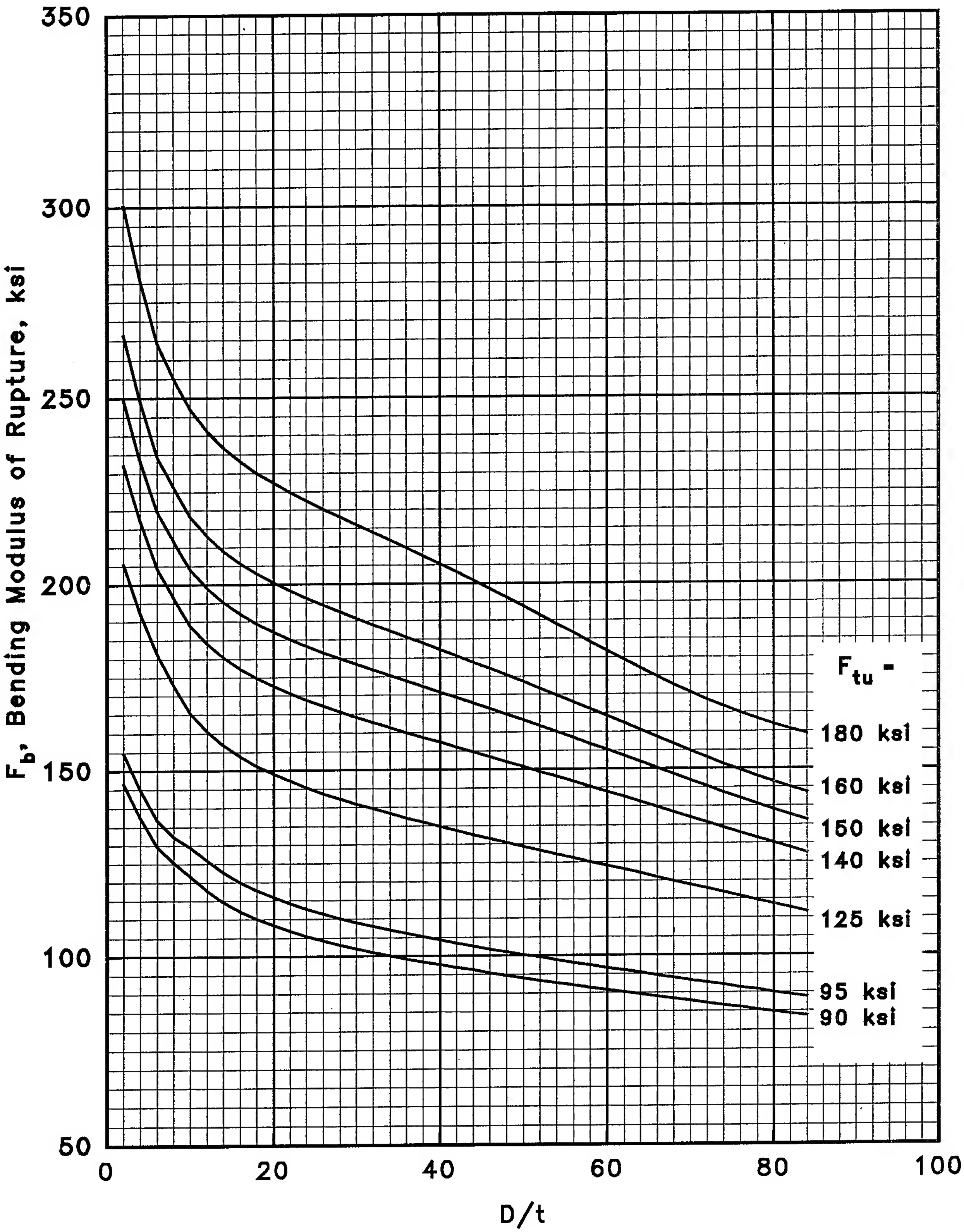

FIGURE 2.8.1.1(a). *Bending modulus of rupture for round low-alloy steel tubing.*

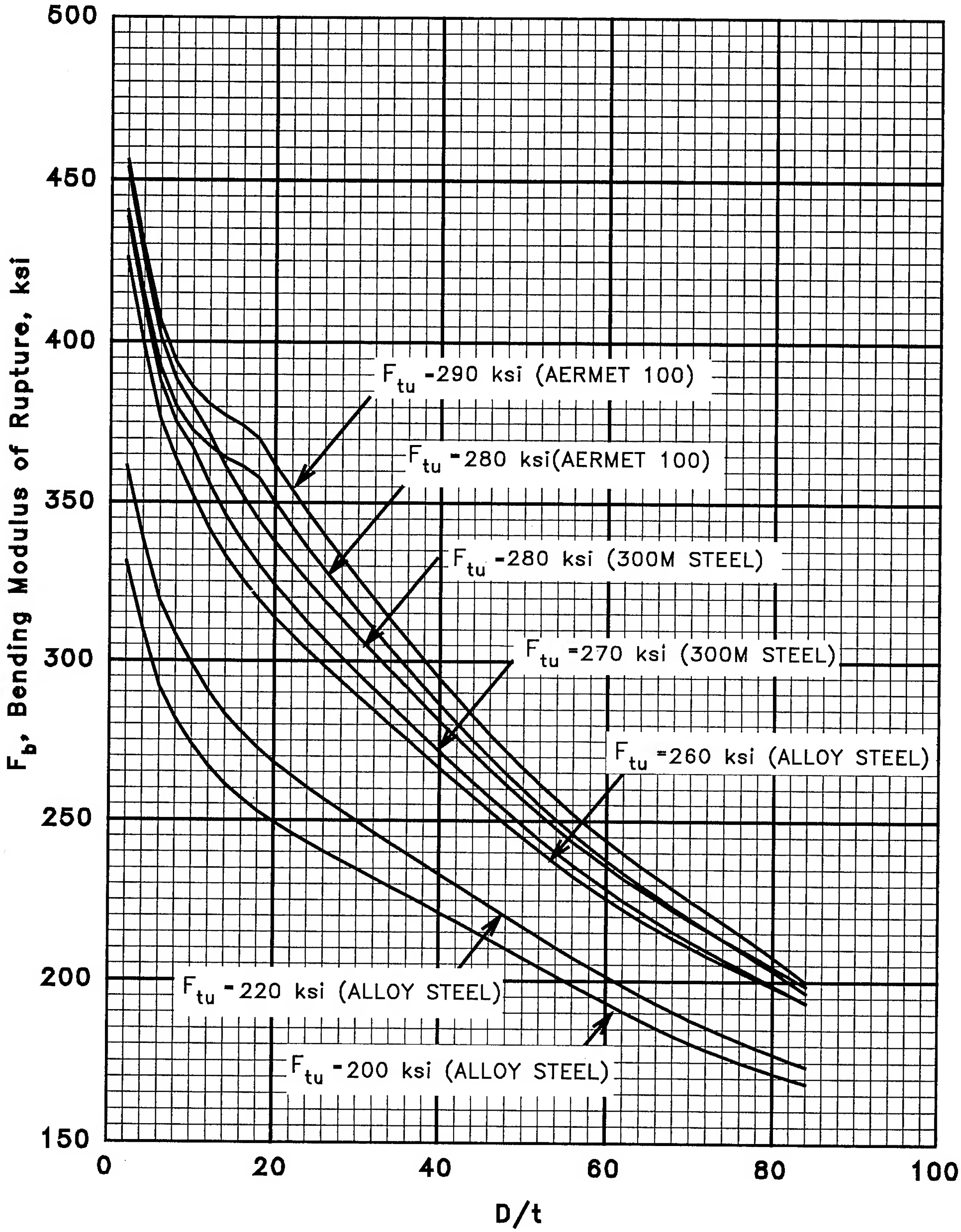

FIGURE 2.8.1.1(b). *Bending modulus of rupture for round high-alloy steel tubing.*

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2.8.3 TORSION

2.8.3.1 *General.*—The torsion failure of steel tubes may be due to material failure, or to elastic or plastic buckling. Pure shear failure usually will not occur within the range of wall thickness commonly used for aircraft tubing.

2.8.3.2 *Torsion Properties.*—The curves of Figures 2.8.3.2(a) through (j) are derived from the method outlined in Reference 2.8.3.2 and take into account the parameter L/D; the theoretical results set forth in Reference 2.8.3.2 have been found to be in good agreement with the experimental results.

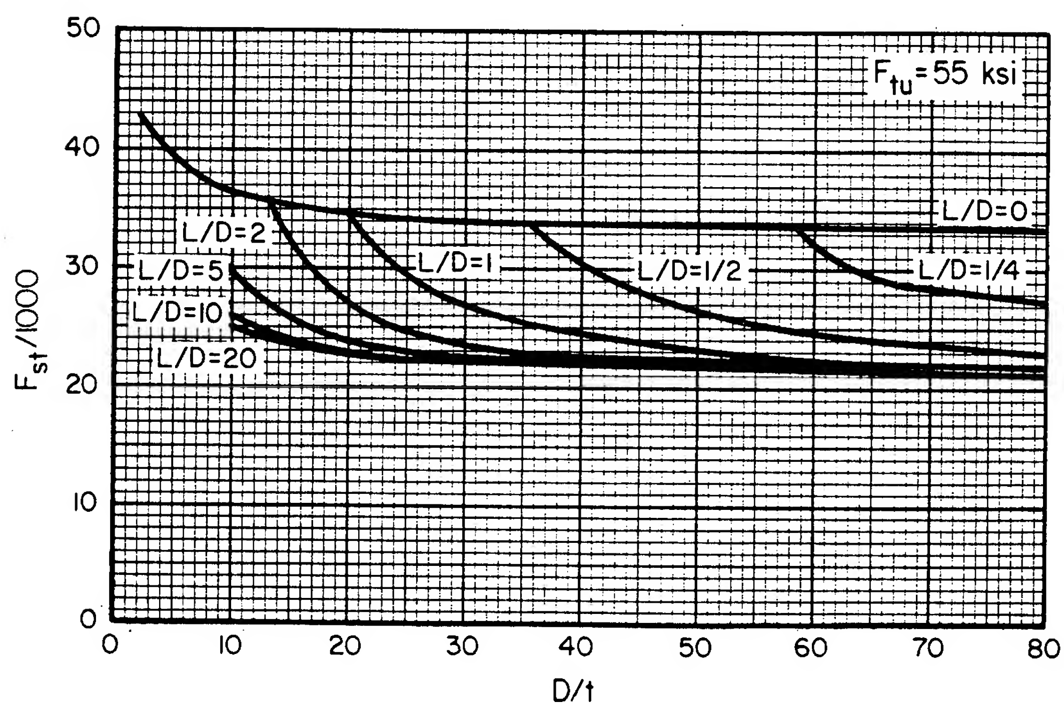

FIGURE 2.8.3.2(a). *Torsional modulus of rupture—plain carbon steels F_{tu} = 55 ksi.*

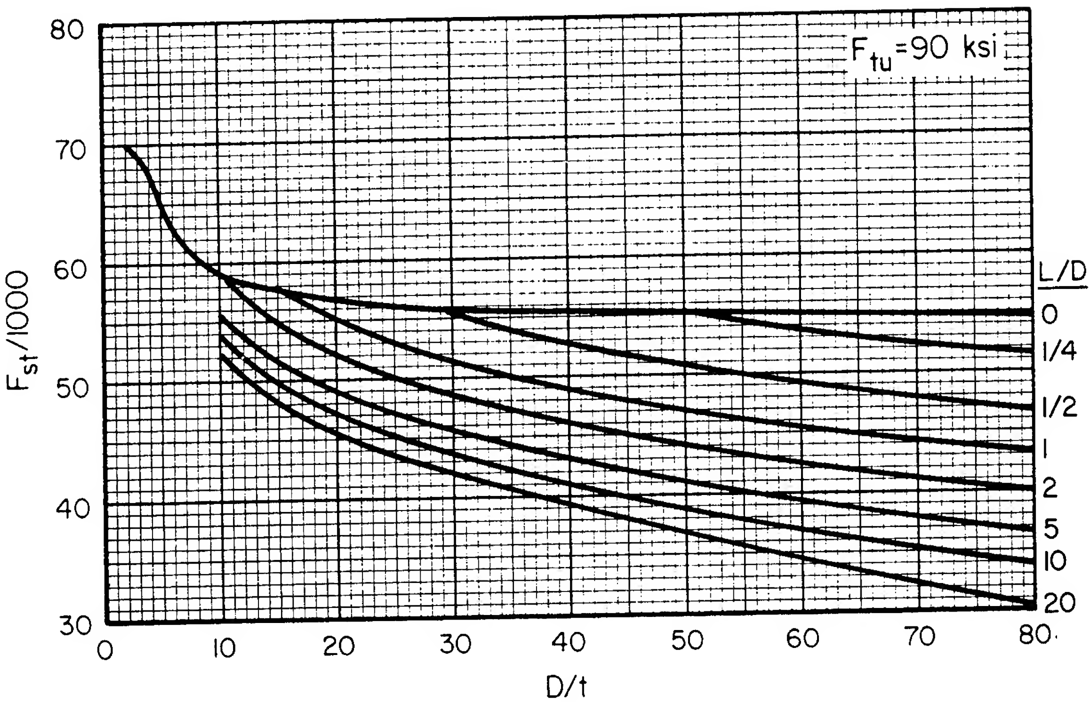

FIGURE 2.8.3.2(b). *Torsional modulus of rupture—low alloy steels treated to F_{tu} = 90 ksi.*

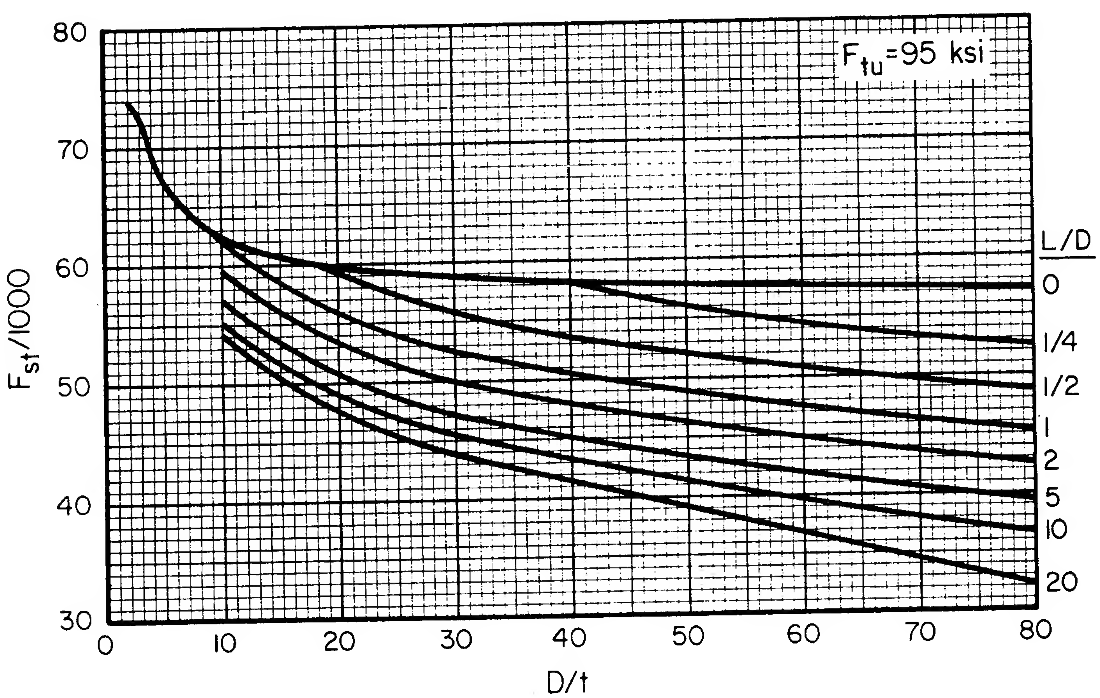

FIGURE 2.8.3.2(c). *Torsional modulus of rupture—low alloy steels heat treated to F_{tu} = 95 ksi.*

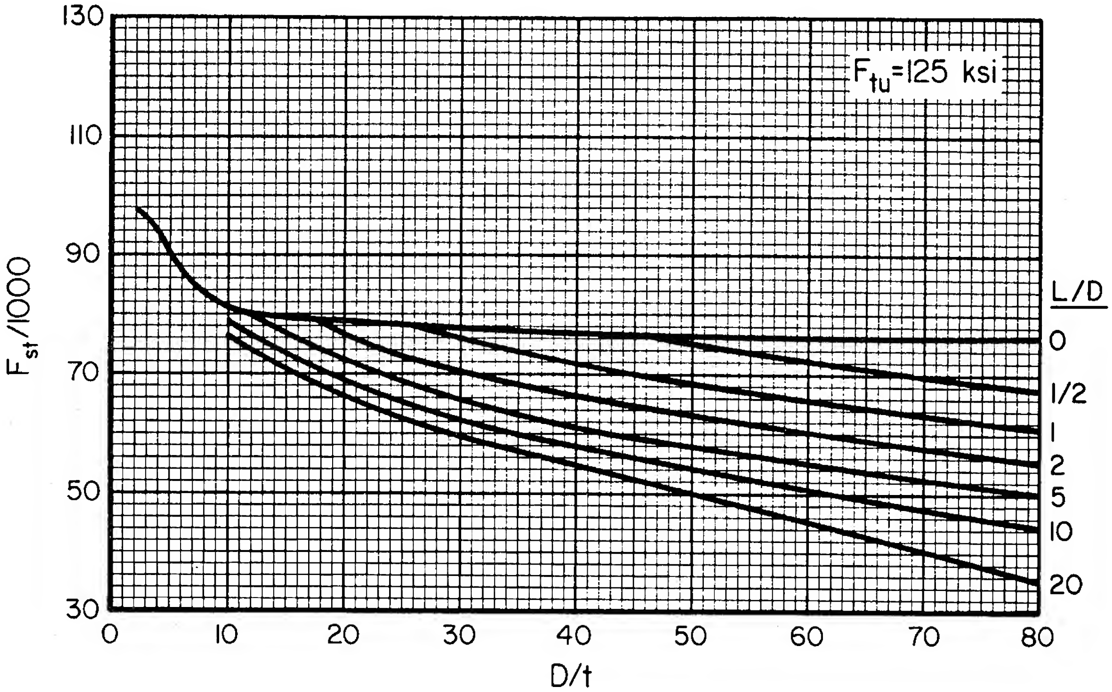

FIGURE 2.8.3.2(d). *Torsional modulus of rupture—low alloy steels, heat treated to F_{tu} = 125 ksi.*

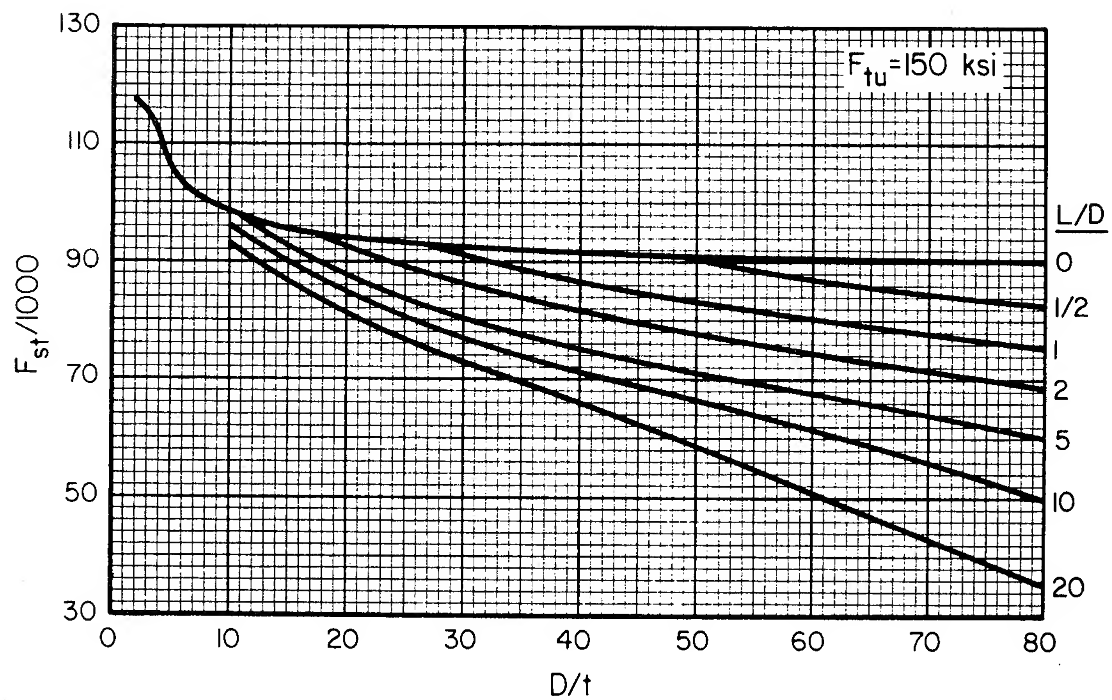

FIGURE 2.8.3.2(e). *Torsional modulus of rupture—low alloy steels heat treated to F_{tu} = 150 ksi.*

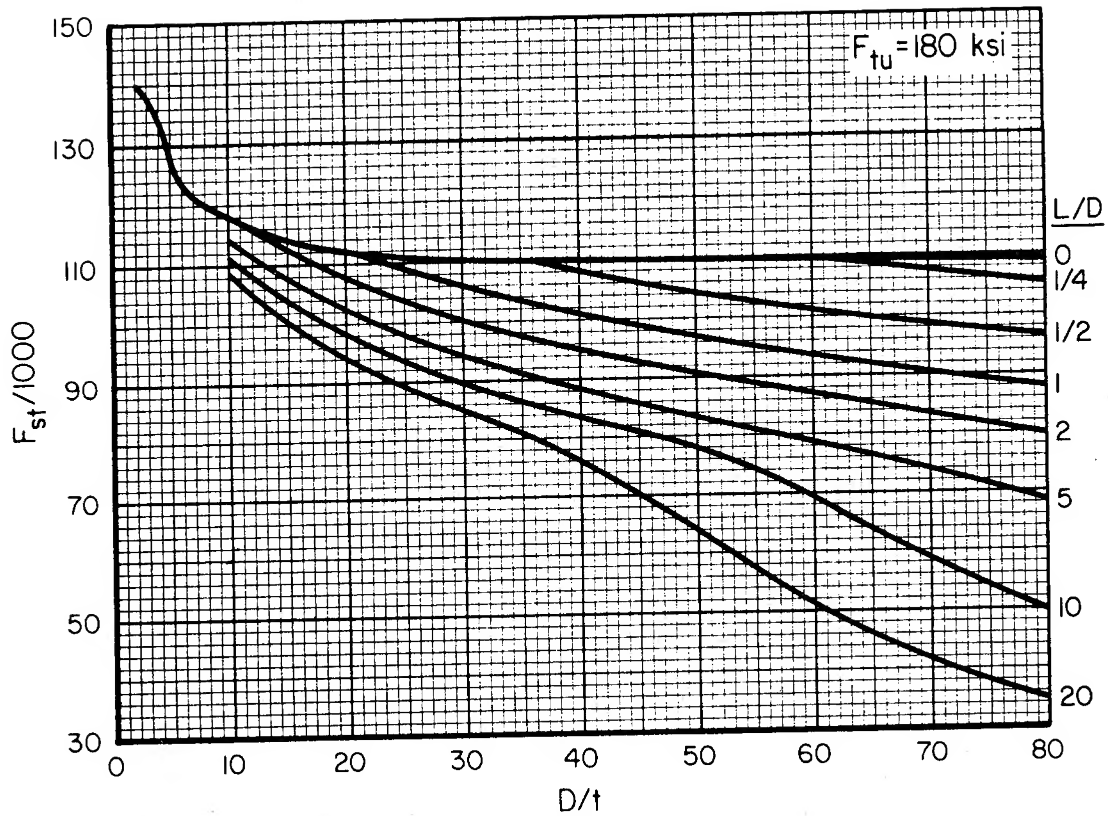

FIGURE 2.8.3.2(f). *Torsional modulus of rupture—alloy steels heat treated to F_{tu} = 180 ksi.*

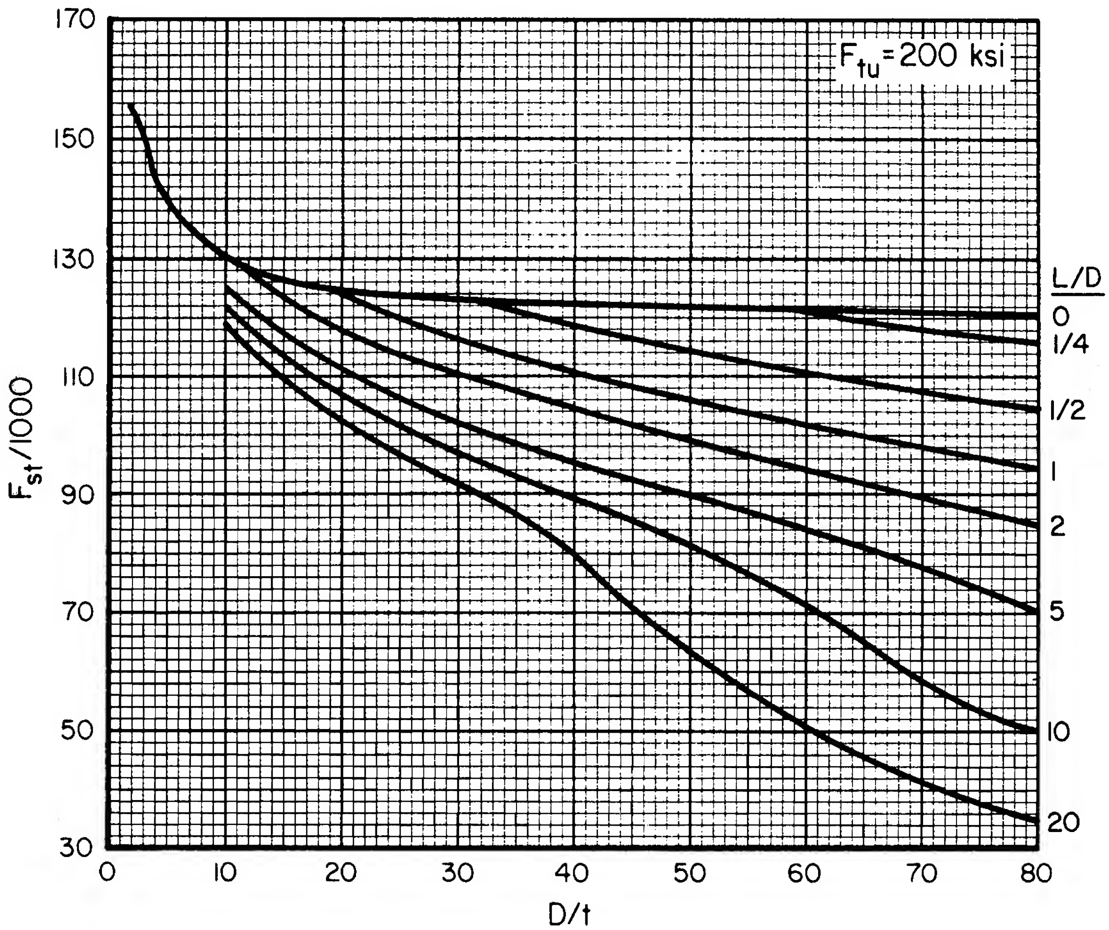

FIGURE 2.8.3.2(g). *Torsional modulus of rupture—alloy steels heat treated to F_{tu}= 200 ksi.*

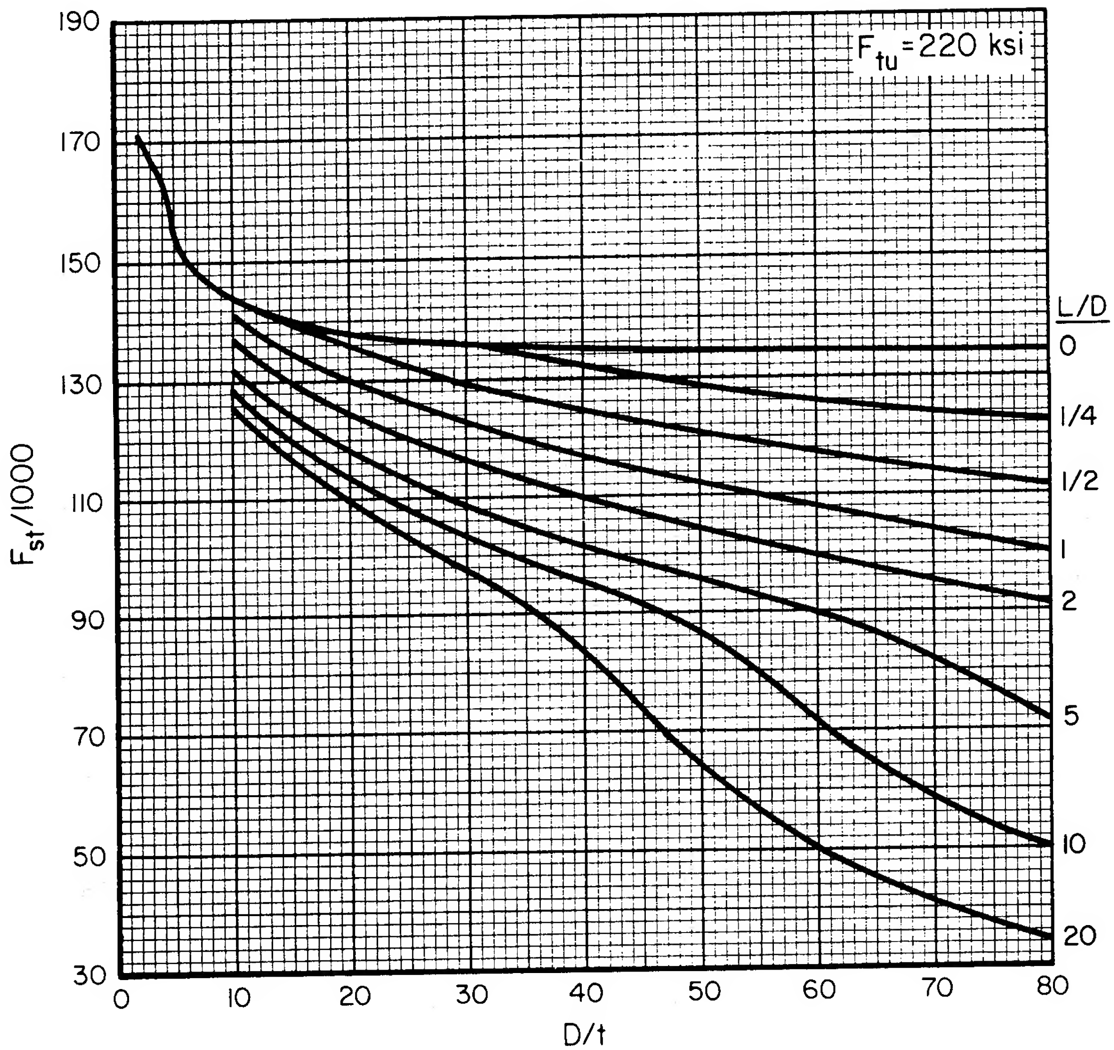

FIGURE 2.8.3.2(h). *Torsional modulus of rupture—alloy steels heat treated to F_{tu}= 220 ksi.*

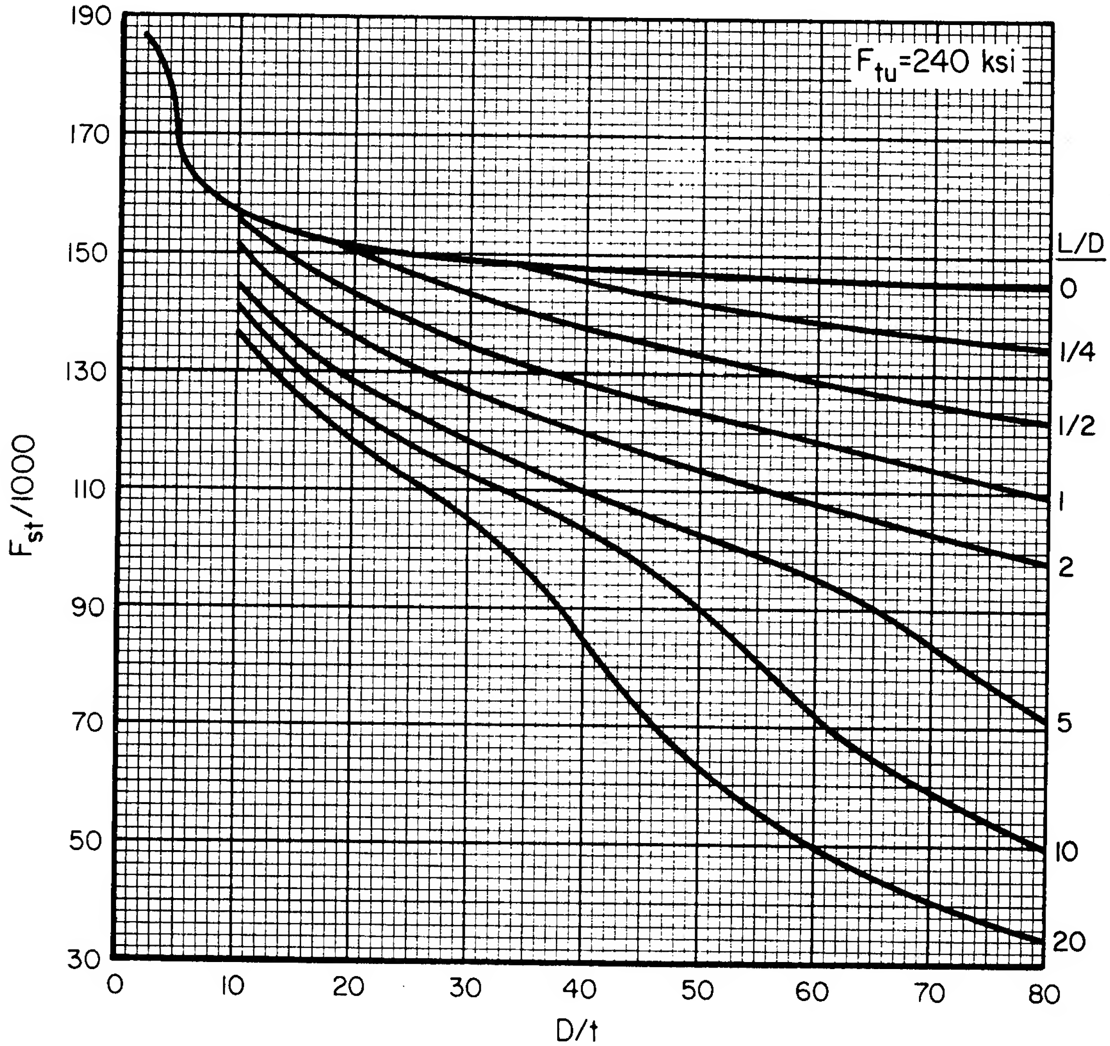

FIGURE 2.8.3.2(i). *Torsional modulus of rupture—alloy steels heat treated to* F_{tu} = *240 ksi.*

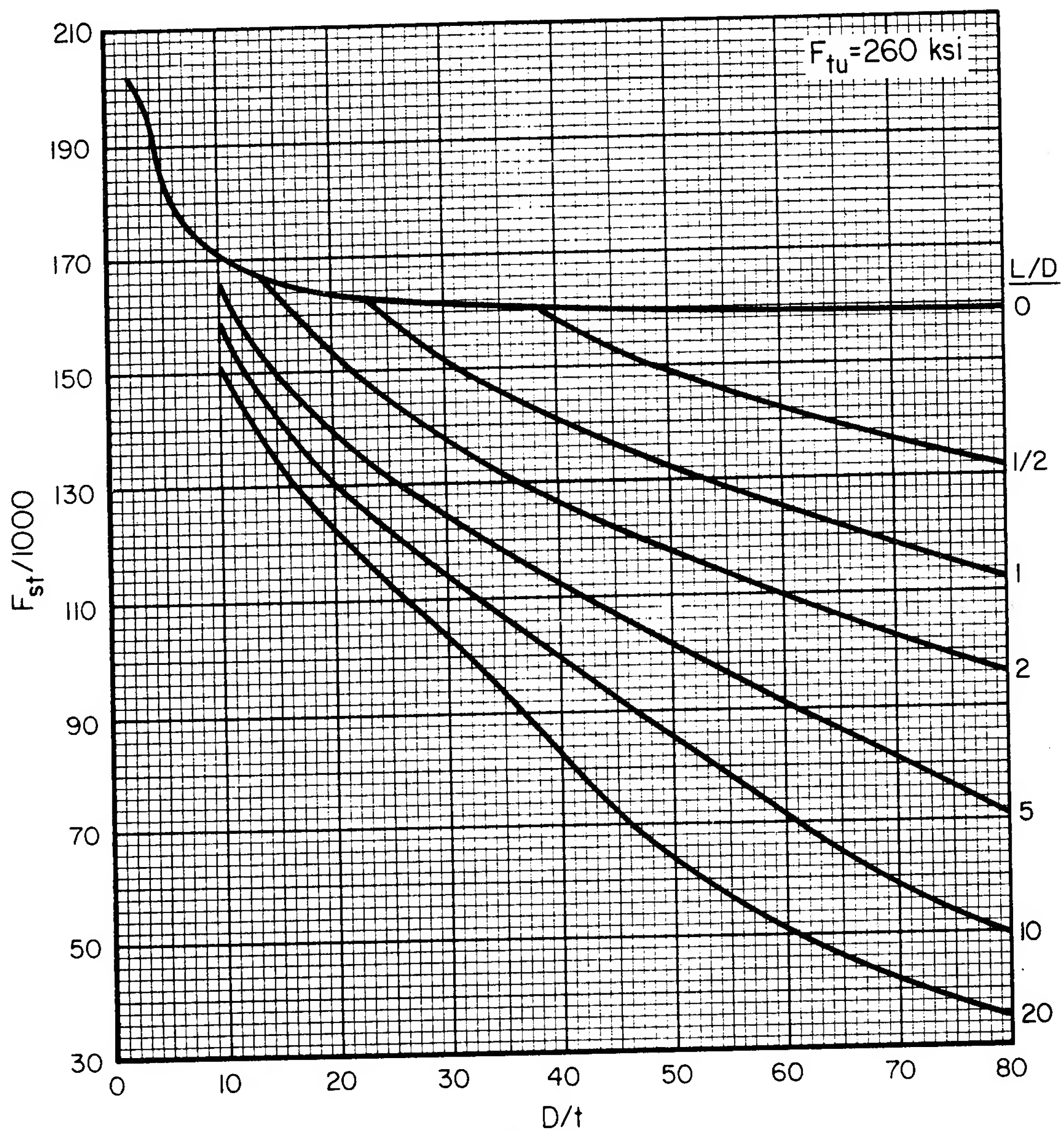

FIGURE 2.8.3.2(j). *Torsional modulus of rupture—alloy steels heat treated to F_{tu} = 260 ksi.*

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Chapter 3

ALUMINUM

3.1 General

This chapter contains the engineering properties and related characteristics of wrought and cast aluminum alloys used in aircraft and missile structural applications.

General comments on engineering properties and the considerations relating to alloy selection are presented in Section 3.1. Mechanical and physical property data and characteristics pertinent to specific alloy groups or individual alloys are reported in Sections 3.2 through 3.10. Element properties are presented in Section 3.11.

Aluminum is a lightweight, corrosion-resistant structural material that can be strengthened through alloying and, dependent upon composition, further strengthened by heat treatment and/or cold working [Reference 3.1(a)]. Among its advantages for specific applications are: low density, high strength-to-weight ratio, good corrosion resistance, ease of fabrication and diversity of form.

Wrought and cast aluminum and aluminum alloys are identified by a four-digit numerical designation, the first digit of which indicates the alloy group as shown in Table 3.1. For structural wrought aluminum alloys the last two digits identify the aluminum alloy. The second digit indicates modifications of the original alloy or impurity limits. For cast aluminum and aluminum alloys the second and third digits identify the aluminum alloy or indicate the minimum aluminum percentage. The last digit, which is to the right of the decimal point, indicates the product form: XXX.0 indicates castings, and XXX.1 and XXX.2 indicate ingot.

3.1.1 ALUMINUM ALLOY INDEX.—The layout of this chapter is in accordance with this four-digit number system for both wrought and cast alloys [Reference 3.1(b)]. Table 3.1.1 is the aluminum alloy index that illustrates both the general section layout as well as details of those specific aluminum alloys presently contained in this chapter. The wrought alloys are in Sections 3.2 through 3.7; whereas the cast alloys are in Sections 3.8 and 3.9.

3.1.2 MATERIAL PROPERTIES.—The properties of the aluminum alloys are determined by the alloy content and method of fabrication. Some alloys are strengthened principally by cold work, while others are strengthened principally by solution heat treatment and precipitation hardening [Reference 3.1(a)]. The temper designations, shown in Table 3.1.2 (which is based on Reference 3.1.2), are indicative of the type of strengthening mechanism employed.

TABLE 3.1. *Basic Designation for Wrought and Cast Aluminum Alloys [Reference 3.1(b)]*

Alloy Group	Major Alloying Elements	Alloy Group	Major Alloying Groups
	Wrought Alloys		Cast Alloys
1XXX	99.00 percent minimum aluminum	1XX.0	99.00 percent minimum aluminum
		2XX.0	Copper
2XXX	Copper	3XX.0	Silicon with added copper and/or magnesium
3XXX	Manganese	4XX.0	Silicon
4XXX	Silicon	5XX.0	Magnesium
5XXX	Magnesium	6XX.0	Unused series
6XXX	Magnesium and Silicon	7XX.0	Zinc
7XXX	Zinc	8XX.0	Tin
8XXX	Other Elements	9XX.0	Other elements
9XXX	Unused series		

TABLE 3.1.1. *Aluminum Alloy Index*

Section	Alloy Designation	Section	Alloy Designation
3.2	2000 series wrought alloys	3.6.3	6151
3.2.1	2014	3.7	7000 series wrought alloys
3.2.2	2107	3.7.1	7010
3.2.3	2024	3.7.2	7049/7149
3.2.4	2025	3.7.3	7050
3.2.5	2090	3.7.4	7075
3.2.6	2124	3.7.5	7150
3.2.7	2219	3.7.6	7175
3.2.8	2519	3.7.7	7475
3.2.9	2618	3.8	200.0 series cast alloys
3.3	3000 series wrought alloys	3.8.1	A201.0
3.4	4000 series wrought alloys	3.9	300.0 series cast alloys
3.5	5000 series wrought alloys	3.9.1	354.0
3.5.1	5052	3.9.2	355.0
3.5.2	5083	3.9.3	C355.0
3.5.3	5086	3.9.4	356.0
3.5.4	5454	3.9.5	A356.0
3.5.5	5456	3.9.6	A357.0
3.6	6000 series wrought alloys	3.9.7	D357.0
3.6.1	6013	3.9.8	359.0
3.6.2	6061		

Among the properties presented herein, some, such as the room-temperature, tensile, compressive, shear and bearing properties, are either specified minimum properties or derived minimum properties related directly to the specified minimum properties. They may be directly useful in design. Data on the effect of temperature on properties are presented so that percentages may be applied directly to the room-temperature minimum properties. Other properties, such as the stress-strain curve, fatigue and fracture toughness data, and modulus of elasticity values, are presented as average or typical values, which may be used in assessing the usefulness of the material for certain applications. Comments on the effect of temperature on properties are given in Sections 3.1.2.1.7 and 3.1.2.1.8; comments on the corrosion resistance are given in Section 3.1.2.3; and comments on the effects of manufacturing practices on these properties are given in Section 3.1.3.

It should be recognized that not all combinations of stress and environment have been investigated, and that it may be necessary to evaluate an alloy under the specific conditions involved for certain critical applications.

3.1.2.1 *Mechanical Properties*

3.1.2.1.1 *Strength (Tension, Compression, Shear, Bearing)*.—The design strength properties at room temperature are listed at the beginning of the section covering the properties of an alloy. The effect of temperature on these properties is indicated in figures which follow the tables.

The A and B values for tensile properties for the direction associated with the specification requirements are based upon a statistical analysis of production quality control data obtained from specimens tested in accordance with procurement specification requirements. For sheet and plate of heat-treatable alloys, the specified minimum values are for the long-transverse (LT) direction, while for sheet and plate of nonheat treatable alloys and for rolled, drawn, or extruded products, the specified minimum values are for the longitudinal (L) direction. For forgings, the specified minimum values are stated for at least two directions. The design tensile properties in other directions and the compression, shear, and bearing properties are "derived" properties, based upon the relationships among the properties developed by tests of at least ten lots of material and applied to the appropriate

TABLE 3.1.2. *Temper Designation System for Aluminum Alloys*

Temper Designation System[ab]

The temper designation system is used for all forms of wrought and cast aluminum and aluminum alloys except ingot. It is based on the sequences of basic treatments used to produce the various tempers. The temper designation follows the alloy designation, the two being separated by a hyphen. Basic temper designations consist of letters. Subdivisions of the basic tempers, where required, are indicated by one or more digits following the letter. These designate specific sequences of basic treatments, but only operations recognized as significantly influencing the characteristics of the product are indicated. Should some other variation of the same sequence of basic operations be applied to the same alloy, resulting in different characteristics, then additional digits are added to the designation.

Basic Temper Designations

F as fabricated. Applies to the products of shaping processes in which no special control over thermal conditions or strain-hardening is employed. For wrought products, there are no mechanical property limits.

O annealed. Applies to wrought products which are annealed to obtain the lowest strength temper, and to cast products which are annealed to improve ductility and dimensional stability. The O may be followed by a digit other than zero.

H strain-hardened (wrought products only). Applies to products which have their strength increased by strain-hardening, with or without supplementary thermal treatments to produce some reduction in strength. The H is always followed by two or more digits.

W solution heat-treated. An unstable temper applicable only to alloys which spontaneously age at room temperature after solution heat-treatment. This designation is specific only when the period of natural aging is indicated: for example, W ½ hr.

T thermally treated to produce stable tempers other than F, O, or H. Applies to products which are thermally treated, with or without supplementary strain-hardening, to produce stable tempers. The T is always followed by one or more digits.

Subdivisions of H Temper: Strain-hardened.

The first digit following H indicates the specific combination of basic operations, as follows:

H1 strain-hardened only. Applies to products which are strain-hardened to obtain the desired strength without supplementary thermal treatment. The number following this designation indicates the degree of strain-hardening.

H2 strain-hardened and partially annealed. Applies to products which are strain-hardened more than the desired final amount and then reduced in strength to the desired level by partial annealing. For alloys that age-soften at room temperature, the H2 tempers have the same minimum ultimate tensile strength as the corresponding H3 tempers. For other alloys, the H2 tempers have the same minimum ultimate tensile strength as the corresponding H1 tempers and slightly higher elongation. The number following this designation indicates the degree of strain-hardening remaining after the product has been partially annealed.

H3 strain-hardened and stabilized. Applies to products which are strain-hardened and whose mechanical properties are stabilized either by a low temperature thermal treatment or as a

[a]From reference 3.1.2.
[b]Temper designations conforming to this standard for wrought aluminum and wrought aluminum alloys, and aluminum alloy castings may be registered with the Aluminum Association provided: (1) the temper is used or is available for use by more than one user, (2) mechanical property limits are registered, (3) characteristics of the temper are significantly different from those of all other tempers which have the same sequence of basic treatments and for which designations already have been assigned for the same alloy and product, and (4) the following are also registered if characteristics other than mechanical properties are considered significant: (a) test methods and limits for the characteristics or (b) the specific practices used to produce the temper.

TABLE 3.1.2. *Temper Designation System for Aluminum Alloys—Continued*

result of heat introduced during fabrication. Stabilization usually improves ductility. This designation is applicable only to those alloys which, unless stabilized, gradually age-soften at room temperature. The number following this designation indicates the degree of strain-hardening remaining after the stabilization treatment.

The digit following the designations H1, H2, and H3 indicates the degree of strain hardening. Numeral 8 has been assigned to indicate tempers having an ultimate tensile strength equivalent to that achieved by a cold reduction (temperature during reduction not to exceed 120 F) of approximately 75 percent following a full anneal. Tempers between O (annealed) and 8 are designated by numerals 1 through 7. Material having an ultimate tensile strength about midway between that of the O temper and that of the 8 temper is designated by the numeral 4; about midway between the O and 4 tempers by the numeral 2; and about midway between 4 and 8 tempers by the numeral 6. Numeral 9 designates tempers whose minimum ultimate tensile strength exceeds that of the 8 temper by 2.0 ksi or more. For two-digit H tempers whose second digit is odd, the standard limits for ultimate tensile strength are exactly midway between those of the adjacent two digit H tempers whose second digits are even.

NOTE: For alloys which cannot be cold reduced an amount sufficient to establish an ultimate tensile strength applicable to the 8 temper (75 percent cold reduction after full anneal), the 6 temper tensile strength may be established by a cold reduction of approximately 55 percent following a full anneal, or the 4 temper tensile strength may be established by a cold reduction of approximately 35 percent after a full anneal.

The third digit[c], when used, indicates a variation of a two-digit temper. It is used when the degree of control of temper or the mechanical properties or both differ from, but are close to, that (or those) for the two-digit H temper designation to which it is added, or when some other characteristic is significantly affected.

NOTE: The minimum ultimate tensile strength of a three-digit H temper must be at least as close to that of the corresponding two-digit H temper as it is to the adjacent two-digit H tempers. Products of the H temper whose mechanical properties are below H_1 shall be variations of H_1.

Three-digit H Tempers

H_11 Applies to products which incur sufficient strain hardening after the final anneal that they fail to qualify as annealed but not so much or so consistent an amount of strain hardening that they qualify as H_1.

H112 Applies to products which may acquire some temper from working at an elevated temperature and for which there are mechanical property limits.

**Subdivisions of T Temper:
Thermally Treated**

Numerals 1 through 10 following the T indicate specific sequences of basic treatments, as follows.[d]

T1 cooled from an elevated temperature shaping process and naturally aged to a substantially stable condition. Applies to products which are not cold worked after cooling from an elevated temperature shaping process, or in which the effect of cold work in flattening or straightening may not be recognized in mechanical property limits.

T2 cooled from an elevated temperature shaping process, cold worked and naturally aged to a substantially stable condition. Applies to products which are cold worked to improve strength after cooling from an elevated temperature shaping process, or in which the effect of

[c]Numerals 1 through 9 may be arbitrarily assigned as the third digit and registered with The Aluminum Association for an alloy and product to indicate a variation of a two-digit H temper (see footnote b).
[d]A period of natural aging at room temperature may occur between or after the operations listed for the T tempers. Control of this period is exercised when it is metallurgically important.

TABLE 3.1.2. *Temper Designation System for Aluminum Alloys—Continued*

cold work in flattening or straightening is recognized in mechanical property limits.

T3 solution heat-treated[e], cold worked, and naturally aged to a substantially stable condition. Applies to products which are cold worked to improve strength after solution heat-treatment, or in which the effect of cold work in flattening or straightening is recognized in mechanical property limits.

T4 solution heat-treated[e] and naturally aged to a substantially stable condition. Applies to products which are not cold worked after solution heat-treatment, or in which the effect of cold work in flattening or straightening may not be recognized in mechanical property limits.

T5 cooled from an elevated temperature shaping process and artificially aged. Applies to products which are not cold worked after cooling from an elevated temperature shaping process, or in which the effect of cold work in flattening or straightening may not be recognized in mechanical property limits.

T6 solution heat-treated[e] and artificially aged. Applies to products which are not cold worked after solution heat-treatment or in which the effect of cold work in flattening or straightening may not be recognized in mechanical property limits.

T7 solution heat-treated[e] and overaged/stabilized. Applies to wrought products that are artificially aged after solution heat-treatment to carry them beyond a point of maximum strength to provide control of some significant characteristic. Applies to cast products that are artificially aged after solution heat-treatment to provide dimensional and strength stability.

T8 solution heat-treated[e], cold worked, and artificially aged. Applies to products which are cold worked to improve strength, or in which the effect of cold work in flattening or straightening is recognized in mechanical property limits.

T9 solution heat-treated[e], artificially aged, and cold worked. Applies to products which are cold worked to improve strength.

T10 cooled from an elevated temperature shaping process, cold worked, and artificially aged. Applies to products which are cold worked to improve strength, or in which the effect of cold work in flattening or straightening is recognized in mechanical property limits.

Additional digits[f], the first of which shall not be zero, may be added to designations T1 through T10 to indicate a variation in treatment which significantly alters the product characteristics[g] that are or would be obtained using the basic treatment.

The following specific additional digits have been assigned for stress-relieved tempers of wrought products:

Stress Relieved by Stretching

T_51 Applies to plate and rolled or cold-finished rod and bar when stretched the indicated amounts after solution heat-treatment or after cooling from an elevated temperature shaping process. The products receive no further straightening after stretching.

[e]Solution heat treatment is achieved by heating cast or wrought products to a suitable temperature, holding at that temperature long enough to allow constituents to enter into solid solution and cooling rapidly enough to hold the constituents in solution. Some 6000 series alloys attain the same specified mechanical properties whether furnace solution heat-treated or cooled from an elevated temperature shaping process at a rate rapid enough to hold constituents in solution. In such cases the temper designations T3, T4, T6, T7, T8, and T9 are used to apply to either process and are appropriate designations.

[f]Additional digits may be arbitrarily assigned and registered with the Aluminum Association for an alloy and product to indicate a variation of tempers T1 through T10 even though the temper representing the basic treatment has not been registered (see footnote b). Variations in treatment which do not alter the characteristics of the product are considered alternate treatments for which additional digits are not assigned.

[g]For this purpose, characteristic is something other than mechanical properties. The test method and limit used to evaluate material for this characteristic are specified at the time of the temper registration.

TABLE 3.1.2. *Temper Designation System for Aluminum Alloys—Continued*

Plate .... 1½ to 3% permanent set.
Rolled or Cold-Finished
Rod and Bar .... 1 to 3% permanent set.
Die or Ring Forgings
and Rolled Rings .... 1 to 5% permanent set.

T_510 Applies to extruded rod, bar, shapes and tube and to drawn tube when stretched the indicated amounts after solution heat-treatment or after cooling from an elevated temperature shaping process. These products receive no further straightening after stretching.

Extruded Rod, Bar, Shapes
and Tube .... 1 to 3% permanent set.
Drawn Tube .... ½ to 3% permanent set.

T_511 Applies to extruded rod, bar, shapes and tube and to drawn tube when stretched the indicated amounts after solution heat-treatment or after cooling from an elevated temperature shaping process. These products may receive minor straightening after stretching to comply with standard tolerances.

Stress Relieved by Compressing

T_52 Applies to products which are stress-relieved by compressing after solution heat-treatment or cooling from an elevated temperature shaping process to produce a set of 1 to 3 percent.

Stress Relieved by Combined Stretching and Compressing

T_54 Applies to die forgings which are stress relieved by restriking cold in the finish die.

NOTE: The same digits (51, 52, 54) may be added to the designation W to indicate unstable solution heat-treated and stress-relieved treatment.

The following temper designations have been assigned for wrought product test material heat-treated from annealed (O, O1, etc.) or F temper.[h]

T42 Solution heat-treated from annealed or F temper and naturally aged to a substantially stable condition.

T62 Solution heat-treated from annealed or F temper and artificially aged.

Temper designations T42 and T62 may also be applied to wrought products heat-treated from any temper by the user when such heat-treatment results in the mechanical properties applicable to these tempers.

Variations of O Temper: Annealed

A digit following the O, when used, indicates a product in the annealed condition have special characteristics. NOTE: As the O temper is not part of the strain-hardened (H) series, variations of O temper shall not apply to products which are strain-hardened after annealing and in which the effect of strain-hardening is recognized in the mechanical properties or other characteristics.

Assigned O Temper Variations

The following temper designation has been assigned for wrought products high temperature annealed to accentuate ultrasonic response and provide dimensional stability.

O1 Thermally treated at approximately same time and temperature required for solution heat treatment and slow cooled to room temperature. Applicable to products which are to be machined prior to solution heat treatment by the user. Mechanical Property limits are not applicable.

Designation of Unregistered Tempers

The letter P has been assigned to denote H, T and O temper variations that are negotiated between manufacturer and purchaser. The letter P immediately follows the temper designation

[h] When the user requires capability demonstrations from T-temper, the seller shall note "capability compliance" adjacent to the specified ending tempers. Some examples are: "-T4 to -T6 Capability Compliance as for aging" or "-T351 to -T4 Capability Compliance as for resolution heat treating."

TABLE 3.1.2. *Temper Designation System for Aluminum Alloys—Continued*

that most nearly pertains. Specific examples where such designation may be applied include the following:	
The use of the temper is sufficiently limited so as to preclude its registration. (Negotiated H temper variations were formerly indicated by the third digit zero.)	The test conditions (sampling location, number of samples, test specimen configuration, etc.) are different from those required for registration with the Aluminum Association.
	The mechanical property limits are not established on the same basis as required for registration with the Aluminum Association.

established A, B, or S properties. All of these properties are representative of the regions from which production quality control specimens are taken, but may not be representative of the entire cross section of products appreciably thicker than the test specimen or products of complex cross sections.

Tensile and compressive strengths are given for the longitudinal, long-transverse, and short-transverse directions wherever data are available. Short-transverse strengths may be relatively low, and transverse properties should not be assumed to apply to the short-transverse direction unless so stated. In those instances where the direction in which the material will be used is not known, the lesser of the applicable longitudinal or transverse properties should be used.

Bearing strengths are given without reference to direction and may be assumed to be about the same in all directions, with the exception of plate, die forging, and hand forging. A reduction factor is used for edgewise bearing load in thick bare and clad plate of 2000 and 7000 series alloys. The results of bearing tests on longitudinal and long-transverse specimens taken edgewise from plate, die forging, and hand forging have shown that the edgewise bearing strengths are substantially lower than those of specimens taken parallel to the surface. The bearing specimen orientations in thick plate are shown in Figure 3.1.2.1.1(a). For plate, bearing specimens are oriented so that the width of the specimen is parallel to the surfaces of the plate (flatwise); consequently, in cases where the stress condition approximates that of the longitudinal or long-transverse edgewise orientations, the reductions in design values shown in Table 3.1.2.1.1 should be made.

It should be noted that in recent years, bearing data have been presented from tests made in accordance with ASTM E 238 which requires clean pins and specimens. See Reference 3.1.2.1.1 for additional information. Designers should consider a reduction factor in applying these values to structural analyses.

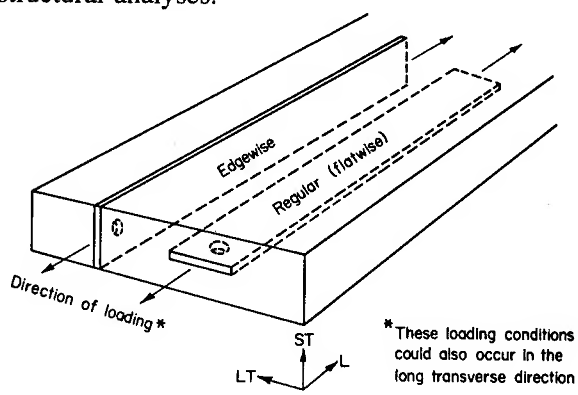

FIGURE 3.1.2.1.1(a). *Bearing specimen orientation in thick plate.*

TABLE 3.1.2.1.1. *Bearing Property Reductions for Thick Plate of 2000 and 7000 Series Alloys*

	Bearing property reduction, percent
Thickness (in.) ...	1.001-6.000
F_{bru} (e/D = 1.5)	15
F_{bru} (e/D = 2.0)	10
F_{bry} (e/D = 1.5)	5
F_{bry} (e.D = 2.0)	5

For die and hand forgings, bearing specimens are taken edgewise so that no reduction factor is necessary. In the case of die forgings, the location of bearing specimens is shown in Figures 3.1.2.1.1(b) and (c). For die forgings with cross-

sectional shapes in the form of an I-beam or a channel, longitudinal bearing specimens are oriented so that the width of the specimens is normal to the parting plane (edgewise). The specimens

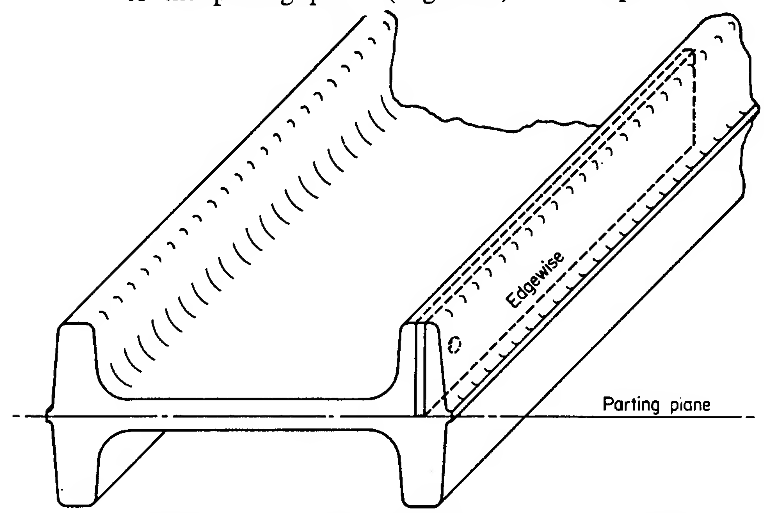

FIGURE 3.1.2.1.1(b). *Bearing specimen orientation for web-flange type die forging.*

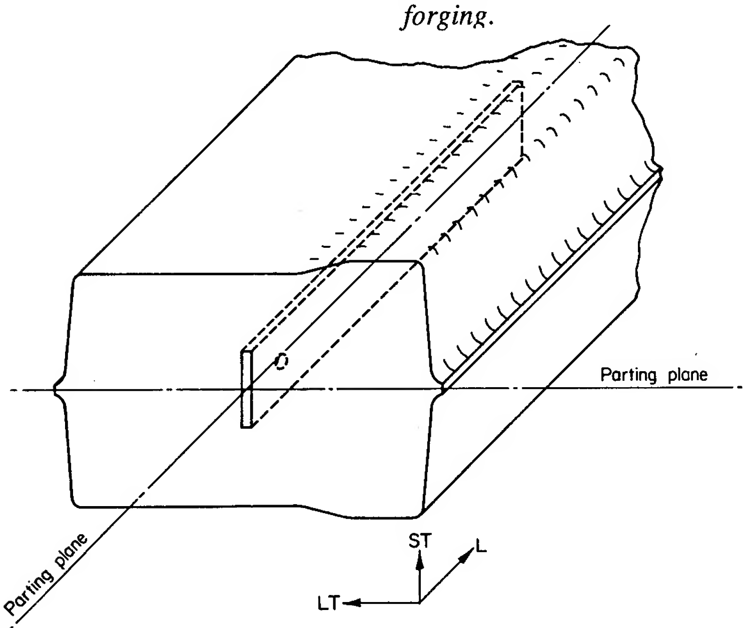

FIGURE 3.1.2.1.1(c). *Bearing specimen orientation for thick-cross section die forging.*

are positioned so that the bearing test holes are midway between the parting plane and the top of the flange. The severity of metal flow at the parting plane near the flash can be expected to vary considerably for web-flange type die forgings; therefore, for consistency, the bearing test hole should not be located on the parting plane. However, in the case of large- bulky-type die forgings, with a cross-sectional shape similar to a square, rectangle, or trapezoid, as shown in Figure 3.1.2.1.1(c), longitudinal bearing specimens are oriented edgewise to the parting plane, but the specimens are positioned so that the bearing test holes are located on the parting plane. Similarly, for hand forgings, bearing specimens are oriented edgewise and the specimens are positioned at the ½ thickness location.

Shear strengths also vary to some extent with plane of shear and direction of loading but the differences are not so consistent [Reference 3.1.2.1.1(c)]. The standard test method for the determination of shear strength of aluminum alloy products, 3/16 inch and greater in thickness, is contained in ASTM B769.

Shear strength values are presented without reference to grain direction, except for hand forgings. For products other than hand forgings, the lowest shear strength exhibited by tests in the various grain directions is the design value. For hand forgings, the shear strength in short-transverse direction may be significantly lower than for the other two grain directions. Consequently, the shear strength for hand forgings is presented for each grain direction.

For clad sheet and plate (i.e., containing thin surface layers of material of a different composition for added corrosion protection), the strength values are representative of the composite (i.e., the cladding and the core). For sheet and thin plate (≤0.499 inch), the quality-control test specimens are of the full thickness, so that the guaranteed tensile properties and the associated derived values for these products directly represent the composite. For plate ≥0.500 inch in thickness, the quality-control test specimens are machined from the core so the guaranteed tensile properties in specifications reflect the core material only, not the composite. Therefore, the design tensile properties for the thicker material are obtained by adjustment of the specification tensile properties and the other related properties to represent the composite, using the nominal total cladding thickness and the typical tensile properties of the cladding material.

For clad aluminum sheet and plate products it is also important to distinguish between primary and secondary modulus values. The initial, or primary, modulus represents an average of the elastic moduli of the core and cladding; it applies only up to the proportional limit of the cladding. For example, the primary modulus of 2024-T3 clad

sheet applies only up to about 6 ksi. Similarly, the primary modulus of 7075-T6 clad sheet applies only up to approximately 12 ksi. A typical use of primary moduli is for low amplitude, high frequency fatigue.

3.1.2.1.2 *Elongation*.—Elongation values are included in the tables of room-temperature mechanical properties. In some cases where the elongation is a function of material thickness, a supplemental table is provided. Short-transverse elongations may be relatively low, and long-transverse values should not be assumed to apply to the short-transverse direction.

3.1.2.1.3 *Stress-Strain Relationship*.—The stress-strain relationships presented, which include elastic and compressive tangent moduli, are typical curves based on three or more lots of test data. Being typical, these curves will not correspond to yield strength data presented as design allowables (minimum values). However, the stress-strain relationships are no less useful, since there are well-known methods for using these curves in design by reducing them to a minimum curve affine to the typical curve or by using Ramberg-Osgood parameters obtained from the typical curves.

3.1.2.1.4 *Creep and Stress Rupture*.—Sustained stressing at elevated temperature sufficient to result in appreciable amounts of creep deformation (e.g., more than 0.2 percent) may result in decreased strength and ductility. It may be necessary to evaluate an alloy under its stress-temperature environment for critical applications where sustained loading is anticipated (see Reference 3.1.2.1.4).

3.1.2.1.5 *Fatigue*.—Fatigue S/N curves are presented for those alloys for which sufficient data are available. Data for both smooth and notched specimens are presented. The data from which the curves were developed were insufficient to establish scatter bands and do not have the statistical reliability of the room-temperature mechanical properties; the values should be considered to be representative for the respective alloys.

The fatigue strengths of aluminum alloys, with both notched and unnotched specimens, are at least as high or higher at subzero temperatures than at room temperature [References 3.1.2.1.5(a) through (c)]. At elevated temperatures, the fatigue strengths are somewhat lower than at room temperature, the difference increasing with increase in temperature.

The data presented do not apply directly to the design of structures because they do not take into account the effect of stress raisers such as reentrant corners, notches, holes, joints, rough surfaces, and other similar conditions which are present in fabricated parts. The localized high stresses induced in fabricated parts by such stress raisers are of much greater importance for repeated loading than they are for static loading and may reduce the fatigue life of fabricated parts far below that which would be predicted by comparing the smooth-specimen fatigue strength directly with the nominal calculated stresses for the parts in question. See References 3.1.2.1.5 (d) through (q) for information on how to use high-strength aluminum alloys, Reference 3.1.2.1.5(r) for details on the static and fatigue strengths of high-strength aluminum-alloy bolted joints, Reference 3.1.2.1.5(s) for single-rivet fatigue-test data, and Reference 1.4.9.3(b) for a general discussion of designing for fatigue. Fatigue-crack-growth data are presented in the various alloy sections.

3.1.2.1.6 *Fracture Toughness*.—Typical values of plane-strain fracture toughness, K_{Ic}, [Reference 3.1.2.1.6(a)] for the high-strength aluminum alloy products are presented in Table 3.1.2.1.6. Minimum, average, and maximum values as well as coefficient of variation are presented for the alloys and tempers for which valid data are available [References 3.1.2.1.6(b) through (j)]. Although representative, these values do not have the statistical reliability of the room-temperature mechanical properties.

Graphic displays of the residual strength behavior of center-cracked tension panels are presented in the various alloy sections. The points denote the experimental data from which the curve of fracture toughness was derived.

3.1.2.1.7 *Cryogenic Temperatures*.—In general, the strengths (including fatigue strengths) of aluminum alloys increase with decrease in temperature below room temperature [References 3.1.2.1.7(a) and (b)]. The increase is greatest over the range from about -100 to -423 F (liquid hydrogen temperature); the strengths at -452 F (liquid helium temperature) are nearly the same as at -423 F [References 3.1.2.1.7(c) and (d)]. For most alloys, elongation and various indices of toughness remain nearly constant or increase with decrease in

TABLE 3.1.2.1.6. *Values of Room-Temperature Plane-Strain Fracture Toughness of Aluminum Alloys*[a]

Alloy/Temper	Product Form	Orientation[b]	Product Thickness Range, inches	Number of Sources	Sample Size	Specimen Thickness Range, inches	K_{Ic}, ksi $\sqrt{in.}$				
							Max.	Avg.	Min.	Coefficient of Variation	Minimum Specification Value
2014-T651	Plate	L-T	$\geq$0.5	1	24	0.5-1.0	25	22	19	8.4	
2014-T651	Plate	T-L	$\geq$0.5	2	34	0.5-1.0	23	21	18	6.5	
2014-T652	Hand Forging	L-T	$\geq$0.5	2	15	0.8-2.0	48	31	24	21.8	
2014-T652	Hand Forging	T-L	$\geq$0.8	2	15	0.8-2.0	30	21	18	14.4	
2024-T351	Plate	L-T	$\geq$1.0	2	11	0.8-2.0	43	31	27	16.5	
2024-T851	Plate	L-S	1.4-3.0	4	11	0.5-0.8	32	25	20	17.8	
2024-T851	Plate	L-T	$\geq$0.5	11	102	0.4-1.4	32	23	15	10.1	
2024-T851	Plate	T-L	0.4-4.0	9	80	0.4-1.4	25	20	18	8.8	
2024-T852	Forging	T-L	2.0-7.0	3	20	0.7-2.0	25	19	15	15.5	
2024-T852	Hand Forging	L-T	-----	4	35	0.8-2.0	38	28	19	18.4	
2024-T852	Hand Forging	T-L	-----	2	17	0.7-2.0	22	18	14	14.4	
2124-T851	Plate	L-T	$\geq$0.8	13	497	0.5-2.5	38	29	18	10.4	24
2124-T851	Plate	T-L	0.6-6.0	10	509	0.5-2.0	32	25	19	9.7	20
2124-T851	Plate	S-L	$\geq$0.5	6	489	0.3-1.5	27	21	16	9.8	18
2219-T851	Plate	L-T	-----	4	67	1.0-2.5	38	33	30	7.2	
2219-T851	Plate	T-L	$\geq$1.0	6	108	0.8-2.5	37	29	20	10.1	
2219-T851	Plate	S-L	$\geq$0.8	3	24	0.5-1.5	26	22	20	9.6	
2219-T851	Forging	S-L	-----	1	85	1.0-1.5	34	25	19	12.1	
2219-T8511	Extrusion	T-L	-----	1	19	1.8-2.0	34	29	23	12.3	
2219-T852	Forging	S-L	-----	2	60	0.8-2.0	35	25	20	12.1	
2219-T852	Hand Forging	L-T	-----	2	32	1.5-2.5	46	38	30	9.7	
2219-T852	Hand Forging	T-L	$\geq$1.5	2	28	1.5-2.5	30	27	22	8.4	
2219-T87	Plate	L-T	$\geq$1.5	3	11	0.8-2.0	34	27	25	9.3	
2219-T87	Plate	T-L	-----	1	11	1.0	22	22	19	3.9	
7049-T73	Die Forging	L-T	1.4	3	21	0.5-1.0	34	30	27	7.4	
7049-T73	Die Forging	S-L	$\geq$0.5	3	46	0.5-1.0	26	22	18	9.7	
7049-T73	Hand Forging	L-T	$\geq$0.5	2	28	0.5-1.0	37	30	23	12.1	
7049-T73	Hand Forging	T-L	2.0-7.1	2	27	1.0	28	22	18	12.5	
7049-T73	Hand Forging	S-L	1.0	2	24	0.8-1.0	22	19	14	14.2	
7050-T7351	Plate	L-T	1.0-6.0	2	31	1.0-2.0	43	35	28	11.3	
7050-T7351	Plate	T-L	2.0-6.0	1	29	1.5-2.0	35	30	25	8.5	
7050-T7351	Plate	S-L	2.0-6.0	1	30	0.8-1.5	30	28	25	4.6	
7050-T74	Die Forging	S-L	0.6-7.1	3	12	0.6-2.0	27	24	21	8.8	

TABLE 3.1.2.1.6. *Values of Room-Temperature Plane-Strain Fracture Toughness of Aluminum Alloys*[a]*--Continued*

Alloy/Temper	Product Form	Orientation[b]	Product Thickness Range, inches	Number of Sources	Sample Size	Specimen Thickness Range, inches	K_{Ic}, ksi $\sqrt{in.}$ Max.	Avg.	Min.	Coefficient of Variation	Minimum Specification Value
7050-T7451	Plate	L-T	-----	13	96	1.0-2.0	39	32	25	11.7	c
7050-T7451	Plate	T-L	≥1.0	9	97	0.5-2.0	38	28	21	15.6	c
7050-T7451	Plate	S-L	≥1.0	6	44	0.7-2.0	28	23	21	6.3	c
7050-T7452	Hand Forging	L-T	3.5-5.5	1	11	1.5	34	31	26	8.0	c
7050-T7452	Hand Forging	T-L	3.5-7.5	1	13	1.5	22	21	18	6.7	c
7050-T7452	Hand Forging	S-L	3.5-7.5	1	17	0 8-1.5	21	19	16	7.5	c
7050-T76511	Extrusion	L-T	-----	2	38	0.6-2.0	40	31	27	7.8	
7075-T651	Plate	L-T	≥0.6	7	99	0.5-2.0	30	26	20	7.6	
7075-T651	Plate	T-L	≥0.5	5	135	0.4-2.0	27	22	18	8.9	
7075-T651	Plate	S-L	-----	2	37	0.5-1.5	22	18	14	10.4	
7075-T6510	Extrusion	L-T	0.7-3.5	1	26	0.5-1.2	32	27	23	7.8	
7075-T6510	Extrusion	T-L	0.7-3.5	1	25	0.5-1.2	28	24	21	8.0	
7075-T6510	Forged Bar	L-T	0.7-5.0	1	13	0.6-2.0	35	29	24	11.6	
7075-T6510	Forged Bar	T-L	0.7-5.0	1	13	0.5-2.5	24	21	17	8.2	
7075-T73	Die Forging	T-L	≥0.5	1	22	0.5-0.8	25	21	18	9.9	
7075-T73	Hand Forging	L-T	-----	2	10	1.0-1.5	39	31	29	8.8	
7075-T73	Hand Forging	T-L	≥1.0	2	14	1.0-1.5	27	23	20	9.0	
7075-T7351	Plate	L-T	≥1.0	8	65	0.5-2.0	36	30	25	8.2	
7075-T7351	Plate	T-L	≥0.5	6	56	0.5-2.0	47	27	21	20.1	
7075-T7351	Plate	S-L	≥0.5	3	20	0.5-1.5	38	22	17	32.5	
7075-T73511	Extrusion	T-L	1.0-7.0	1	19	0.9-1.0	22	20	19	3.7	
7075-T73511	Extrusion	L-T	≥0.9	3	28	0.7-2.0	43	35	31	9.4	
7075-T73511	Extrusion	T-L	≥0.7	3	35	0.5-1.8	35	23	12	20.3	
7075-T73511	Extrusion	S-L	≥0.5	3	15	0.4-1.0	22	20	17	9.0	
7075-T7352	Hand Forging	L-T	-----	2	27	0.8-2.0	39	33	30	9.2	
7075-T7352	Hand Forging	T-L	≥0.8	3	20	0.8-2.0	33	26	23	9.9	
7075-T7651	Plate	L-T	≥0.8	6	82	0.5-2.0	43	29	22	17.8	
7075-T7651	Plate	T-L	≥0.5	7	96	0.5-2.0	28	23	20	7.6	
7075-T7651	Plate	S-L	≥0.5	5	28	0.4-0.8	20	18	15	7.7	
7075-T7651	Clad Plate	L-T	0.5-0.6	2	30	0.5-0.6	30	25	22	7.1	
7075-T7651	Clad Plate	T-L	0.5-0.6	2	56	0.5-0.6	28	24	21	7.7	
7075-T76511	Extrusion	L-T	1.3-7.0	4	11	1.2-2.0	41	35	31	11.0	
7075-T76511	Extrusion	T-L	1.2	3	42	0.6-2.0	36	23	20	15.5	

TABLE 3.1.2.1.6. *Values of Room-Temperature Plane-Strain Fracture Toughness of Aluminum Alloys[a]--Continued*

Alloy/Temper	Product Form	Orientation[b]	Product Thickness Range, inches	Number of Sources	Sample Size	Specimen Thickness Range, inches	K_{Ic}, ksi $\sqrt{in.}$ Max.	Avg.	Min.	Coefficient of Variation	Minimum Specification Value
7175-T6/T6511	Extrusion	T-L	-----	2	25	0.8-1.0	24	21	18	7.9	
7175-T651	Plate	L-T	-----	1	17	0.7-0.8	30	26	24	9.2	
7175-T651	Plate	T-L	-----	1	10	0.7-0.8	26	22	20	9.8	
7175-T6511	Extrusion	L-T	-----	2	14	0.8-1.0	36	32	24	13.8	
7175-T7351	Plate	L-T	-----	2	30	0.7-1.6	36	33	32	3.3	
7175-T7351	Plate	T-L	-----	2	32	0.7-1.6	30	27	25	4.5	
7175-T73511	Extrusion	L-T	$\geq$0.7	5	43	0.5-1.5	47	33	23	16.0	30
7175-T73511	Extrusion	T-L	$\geq$0.5	5	43	0.5-1.5	35	25	20	10.9	22
7175-T74	Die Forging	L-T	$\geq$0.5	3	14	0.5-1.0	38	30	22	15.0	27
7175-T74	Die Forging	T-L	$\geq$0.5	2	13	0.5-1.0	33	24	21	15.7	21
7175-T74	Die Forging	S-L	$\geq$0.5	4	41	0.5-0.8	31	26	20	8.6	21
7175-T74	Hand Forging	T-L	3.0-5.0	2	10	1.0-1.5	29	26	24	4.8	25
7175-T7651	Clad Plate	L-T	-----	1	53	1.5	33	32	30	4.3	
7175-T7651	Clad Plate	T-L	-----	1	50	0.6	28	27	25	3.1	
7175-T7651	Plate	L-T	-----	1	12	1.5	32	32	31	1.7	
7175-T7651	Plate	T-L	-----	1	11	1.5	26	25	24	3.3	
7175-T76511	Extrusion	L-T	1.4-3.8	2	48	0.6-2.0	39	33	27	10.7	
7175-T76511	Extrusion	T-L	$\geq$0.6	4	49	0.6-1.8	31	22	20	9.8	
7475-T651	Plate	L-T	-----	3	34	0.9-2.0	49	38	33	9.2	30
7475-T651	Plate	T-L	0.6-2.0	2	143	0.6-2.0	43	34	27	9.8	28
7475-T651	Plate	S-L	$\geq$0.6	1	23	0.5-1.0	36	28	20	14.9	
7475-T7351	Plate	L-T	1.3-4.0	8	151	1.3-3.0	60	47	34	10.4	c
7475-T7351	Plate	T-L	$\geq$1.3	7	132	0.7-3.0	50	37	29	10.4	c
7475-T7351	Plate	S-L	$\geq$0.7	7	74	0.5-1.5	36	30	25	8.7	25
7475-T7651	Plate	L-T	1.0-2.0	4	10	1.0-2.0	46	41	36	6.2	33
7475-T7651	Plate	T-L	$\geq$1.0	2	15	0.9-2.0	50	36	29	14.5	30

[a] These values are for information only.
[b] Refer to Figure 1.4.12.3 for definition of symbols.
[c] Varies with thickness.

temperature, while for the 7000 series, modest reductions are observed [References 3.1.2.1.7(d) and (e)]. None of the alloys exhibit a marked transition in fracture resistance over a narrow range of temperature indicative of embrittlement.

The tensile and shear moduli of aluminum alloys also increase with decreasing temperature so that at -100, -320, and -423 F, they are approximately 5, 12, and 16 percent, respectively, above the room temperature values [Reference 3.1.2.1.7(f)].

3.1.2.1.8 *Elevated Temperatures.*—In general, the strengths of aluminum alloys decrease and toughness increases with increase in temperature and with time at temperature above room temperature; the effect is generally greatest over the temperature range from 212 to 400 F. Exceptions to the general trends are tempers developed by solution heat treatment without subsequent aging, for which the initial elevated temperature exposure results in some age hardening and reduction in toughness; further time at temperature beyond that required to achieve peak hardness results in the aforementioned decrease in strength and increase in toughness [Reference 3.1.2.1.8].

3.1.2.2 *Physical Properties.*—Where available from the literature, the average values of certain physical properties are included in the room-temperature tables for each alloy. These properties include density, ω, in lb/in.^{3}; the specific heat, C, in Btu (lb)(F); the thermal conductivity, K, in Btu [(hr)(ft^2)(F)/ft]; and the mean coefficient of thermal expansion, α, in in./in./F. Where more extensive data are available to show the effect of temperature on these physical properties, graphs of physical property as a function of temperature are presented for the applicable alloys.

3.1.2.3 *Corrosion Resistance*

3.1.2.3.1 *Resistance to Stress-Corrosion Cracking [see References 3.1.2.3.1(a) through (d)].*—The high-strength heat treatable wrought aluminum alloys in certain tempers are susceptible to stress-corrosion cracking, depending upon product, section size, direction and magnitude of stress. These alloys include 2014, 2025, 2618, 7075, 7150, 7175, and 7475 in the T6-type tempers and 2014, 2024, 2124, and 2219 in the T3 and T4-type tempers. Other alloy-temper combinations, notably 2024, 2124, 2219, and 2519 in the T6- or T8-type tempers and 7010, 7049, 7050, 7075, 7149, 7175, and 7475 in the T73-type tempers, are decidedly more resistant and sustained tensile stresses of 50 to 75 percent of the minimum yield stength may be permitted without concern about stress corrosion cracking. The T74 and T76 tempers of 7010, 7075, 7475, 7049, 7149, and 7050 provide an intermediate degree of resistance to stress-corrosion cracking, i.e., superior to that of the T6 temper, but not as good as that of the T73 temper of 7075. To assist in the selection of materials, letter ratings indicating the relative resistance to stress-corrosion cracking of various mill product forms of the wrought 2000, 6000, and 7000 series heat-treated aluminum alloys are presented in Table 3.1.2.3.1(a). This table is based upon ASTM G64 which contains more detailed information regarding this rating system and the procedure for determining the ratings. In addition, more quantitative information in the form of the maximum specified tension stresses at which test specimens will not fail when subjected to the alternate immersion stress-corrosion test described in ASTM G47 are shown in Tables 3.1.2.3.1(b) through (e) for various heat-treated aluminum product forms, alloys, and tempers.

Where short times at elevated temperatures of 150 to 500 F may be encountered, the precipitation heat-treated tempers of 2024 and 2219 alloys are recommended over the naturally aged tempers.

Alloys 5083, 5086, and 5456 should not be used under high constant applied stress for continuous service at temperatures exceeding 150 F, because of the hazard of developing susceptibility to stress-corrosion cracking. In general, the H34 through H38 tempers of 5086, and the H32 through H38 tempers of 5083 and 5456 are not recommended, because these tempers can become susceptible to stress-corrosion cracking.

For the cold forming of 5083 sheet and plate in the H112, H321, H323, and H343 tempers and 5456 sheet and plate in the H112 and H321 tempers, a minimum bend radius of 5T should be used. Hot forming of the O temper for alloys 5083 and 5456 is recommended, and is preferred to the cold worked tempers to avoid excessive cold work and high residual stress. If the cold worked tempers are heat-treatable alloys are heated for hot forming, a slight decrease in mechanical properties, particularly yield strength, may result.

3.1.2.3.2 *Resistance to Exfoliation [Reference 3.1.2.3.2].*—The high-strength wrought aluminum

TABLE 3.1.2.3.1(a). *Resistance to Stress-Corrosion Ratings[a] for High-Strength Aluminum Alloy Products*

Alloy and Temper[b]	Test Direction[c]	Rolled Plate	Rod and Bar[d]	Extruded Shapes	Forging
2014-T6	L	A	A	A	B
	LT	B[e]	D	B[e]	B[e]
	ST	D	D	D	D
2024-T3, T4	L	A	A	A	f
	LT	B[e]	D	B[e]	f
	ST	D	D	D	f
2024-T6	L	f	A	f	A
	LT	f	B	f	A[e]
	ST	f	B	f	D
2024-T8	L	A	A	A	A
	LT	A	A	A	A
	ST	B	A	B	C
2124-T8	L	A	f	f	f
	LT	A	f	f	f
	ST	B	f	f	f
2219-T351X, T37	L	A	f	A	f
	LT	B	f	B	f
	ST	D	f	D	f
2219-T6	L	A	A	A	A
	LT	A	A	A	A
	ST	A	A	A	A
2219-T85XX, T87	L	A	f	A	A
	LT	A	f	A	A
	ST	A	f	A	A
6061-T6	L	A	A	A	A
	LT	A	A	A	A
	ST	A	A	A	A
7049-T73	L	A	f	A	A
	LT	A	f	A	A
	ST	A	f	B	A
7049-T76	L	f	f	A	f
	LT	f	f	A	f
	ST	f	f	C	f
7050-T74	L	A	f	A	A
	LT	A	f	A	A
	ST	B	f	B	B
7050-T76	L	A	A	A	f
	LT	A	B	A	f
	ST	C	B	C	f
7075-T6	L	A	A	A	A
	LT	B[e]	D	B[e]	B[e]
	ST	D	D	D	D
7075-T73	L	A	A	A	A
	LT	A	A	A	A
	ST	A	A	A	A

TABLE 3.1.2.3.1(a). *Resistance to Stress-Corrosion Ratings[a] for High-Strength Aluminum Alloy Products—Continued*

Alloy and Temper[b]	Test Direction[c]	Rolled Plate	Rod and Bar[d]	Extruded Shapes	Forging
7075-T74	L	f	f	f	A
	LT	f	f	f	A
	ST	f	f	f	B
7075-T76	L	A	f	A	f
	LT	A	f	A	f
	ST	C	f	C	f
7149-T73	L	f	f	A	A
	LT	f	f	A	A
	ST	f	f	B	A
7175-T4	L	f	f	f	A
	LT	f	f	f	A
	ST	f	f	f	B
7475-T6	L	A	f	f	f
	LT	B[e]	f	f	f
	ST	D	f	f	f
7475-T73	L	A	f	f	f
	LT	A	f	f	f
	ST	A	f	f	f
7475-T76	L	A	f	f	f
	LT	A	f	f	f
	ST	C	f	f	f

[a]Ratings were determined from stress corrosion tests performed on at least ten random lots for which test results showed 95% conformance at the 95% confidence level when tested at the indicated stresses below. A practical interpretation of these ratings follows the rating definition.

A - Equal or greater than 75% of the specified minimum yield strength. Very high. No record of service problems and SCC not anticipated in general applications.

B - Equal or greater than 50% of the specified minimum yield strength. High. No record of service problems and SCC not anticipated at stresses of the magnitude caused by solution heat treatment. Precautions must be taken to avoid high sustained tensile stress exceeding 50% of the minimum specified yield strength produced by any combination of sources including heat treatment, straightening, forming, fit-up, and sustained service loads.

C - Equal or greater than 25% of the specified minimum yield strength. Intermediate. SCC not anticipated if the total sustained tensile strength is less than 25% of the minimum specified yield strength. This rating is designated for the short transverse direction in improved products used primarily for high resistance to exfoliation corrosion in relatively thin structures where applicable short transverse stresses are unlikely.

D - Fails to meet the criterion for the rating C. Low. SCC failures have occurred in service or would be anticipated if there is any sustained tensile stress in the designated test direction. This rating currently is designated only for the short transverse direction in certain materials.

NOTE - The above stress levels are not to be interpreted as "threshold" stresses, and are not recommended for design. Other documents, such as MIL-STD-1568, NAS SD-24, and MSFC-SPEC-522A, should be consulted for design recommendations.

TABLE 3.1.2.3.1(a). *Resistance to Stress-Corrosion Ratings[a] for High Strength Aluminum Alloy Products—Continued*

[b]The ratings apply to standard mill products in the types of tempers indicated, including stress-relieved tempers, and could be invalidated in some cases by application of nonstandard thermal treatments of mechanical deformation at room temperature by the user.

[c]Test direction refers to orientation of the stressing direction relative to the directional grain structure typical of wrought materials, which in the case of extrusions and forgings may not be predictable from the geometrical cross section of the product.

L—Longitudinal: parallel to the direction of principal metal extension during manufacture of the product.

LT—Long Transverse: perpendicular to direction of principal metal extension. In products whose grain structure clearly shows directionality (width to thickness ratio greater than two) it is that perpendicular direction parallel to the major grain dimension.

ST—Short Transverse: perpendicular to direction of principal metal extension and parallel to minor dimension of grains in products with significant grain directionality.

[d]Sections with width-to-thickness ratio equal to or less than two for which there is no distinction between LT and ST.

[e]Rating is on class lower for thicker sections: extrusion, 1 inch and over; plate and forgings, 1.5 inches and over.

[f]Ratings not established because the product is not offered commercially.

NOTE: This table is based upon ASTM G64.

TABLE 3.1.2.3.1(b). *Maximum Specified Tension Stress at Which Test Specimens Will Not Fail in 3½% NaCl Alternate Immersion Test[d] for Various Stress Corrosion Resistant Aluminum Alloy Plate*

Alloy and Temper	Test Direction	Thickness, inches	Stress, ksi	Referenced Specifications
2024-T851	ST	1.001-4.000	28[a]	Company specification
		4.001-6.000	27[a]	
2090-T81[c]	ST	0.750-1.500	20	AMS 4303
2124-T851	ST	1.500-1.999	28[a]	AMS 4101
		2.000-4.000	28[a]	QQ-A-0025/29, ASTM B209, AMS 4101
		4.001-6.000	27[a]	
2124-T8151[c]	ST	1.500-3.000	30[a]	AMS 4221
		3.001-5.000	29[a]	
		5.001-6.000	28[a]	
2219-T851	ST	0.750-2.000	34[b]	QQ-A-250/30
		2.001-4.000	33[b]	
		4.001-5.000	32[b]	
		5.001-6.000	31[b]	
2219-T87	ST	0.750-3.000	38[b]	QQ-A-250/30
		3.001-4.000	37[b]	
		4.001-5.000	36[b]	
2519-T87	ST	0.750-4.000	43[b]	MIL-A-46192
7010-T7351[c]	ST	0.750-3.000	41[b]	AMS 4203
		3.001-5.000	40[b]	
		5.001-5.500	39[b]	
7010-T7451	ST	0.750-3.000	31[a]	AMS 4205
		3.001-5.500	35	
7010-T7651	ST	0.750-5.500	25	AMS 4204
7049-T7351	ST	0.750-5.000	45	AMS 4200
7050-T7451	ST	0.750-6.000	35	AMS 4050
7050-T7651	ST	0.750-3.000	25	AMS 4201
7075-T7351	ST	0.750-2.000	42[b]	QQ-A-250/12, AMS 4078, ASTM B209
		2.001-2.500	39[b]	
		2.501-4.000	36[b]	
7075-T7651	ST	0.750-1.000	25	QQ-A-00250/24, ASTM B209
Clad 7075-T7651	ST	0.750-1.000	25	QQ-A-00250/25, ASTM B209
7150-T7751	ST	0.750-3.000	25	AMS 4252
7475-T7351	ST	0.750-4.000	40	AMS 4202
7475-T7651	ST	0.750-1.500	25	AMS 4089

[a]50% of specified minimum long transverse yield strength.
[b]75% of specified minimum long transverse yield strength.
[c]Design values are not included in MIL-HDBK-5.
[d]Most specifications reference ASTM G-47, which requires exposures of 10 days for 2XXX alloys and 20 days for 7XXX alloys in ST test direction.

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TABLE 3.1.2.3.1(c). *Maximum Specified Tension Stress at Which Test Specimens Will Not Fail in 3½% NaCl Alternate Immersion Test[e] for Various Stress Corrosion Resistant Aluminum Alloy Rolled Bars, Rods, and Extrusions*

Alloy and Temper	Product Form	Test Direction	Thickness, inches	Stress, ksi	Referenced Specifications
7075-T73-T7351	Rolled Bar and Rod	ST	0.750-3.000	42[a]	QQ-A-225/9, AMS 4124, ASTM B211
2219-T8511	Extrusion	ST	0.750-3.000	30	AMS 4162, AMS 4163
7049-T73511	Extrusion	ST	0.750-2.999	41[b]	AMS 4157
			3.000-5.000	40[b]	
7049-T76511[d]	Extrusion	ST	0.750-5.000	20	AMS 4159
7050-T73511	Extrusion	ST	0.750-5.000	45	AMS 4341
7050-T74511	Extrusion	ST	0.750-5.000	35	AMS 4342
7050-T76511	Extrusion	ST	0.750-5.000	17	AMS 4340
7075-T73-T73510-T73511	Extrusion	ST	0.750-1.499	45[a]	QQ-A-200/11, AMS 4166, AMS 4167, ASTM B211
			1.500-2.999	44[a]	
			3.000-4.999	42[a]	
			3.000-4.999	41[a,c]	
7075-T76-T76510-T76511	Extrusion	ST	0.750-1.000	25	QQ-A-200/15, ASTM B221
7149-T73511[d]	Extrusion	ST	0.750-2.999	41[b]	AMS 4543
			3.000-5.000	40[b]	
7150-T77511	Extrusion	ST	0.750-2.000	25	AMS 4345
7175-T73511	Extrusion	ST	0.750-2.000	44	AMS 4344

[a] 75% of specified minimum longitudinal yield strength.
[b] 65% of specified minimum longitudinal yield strength.
[c] Over 20 square inches cross-sectional area.
[d] Design values are not included in MIL-HDBK-5.
[e] Most specifications reference ASTM G47, which requires exposures of 10 days for 2XXX alloys and 20 days for 7XXX alloys in ST test direction.

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TABLE 3.1.2.3.1(d). *Maximum Specified Tension Stress at Which Test Specimens Will Not Fail in 3½% NaCl Alternate Immersion Test[d] for Various Stress Corrosion Resistant Aluminum Die Forgings*

Alloy and Temper	Test Direction	Thickness, inches	Stress, ksi	Referenced Specifications
7049-T73	ST	0.750-2.000	46[a]	QQ-A-367, AMS 4111, ASTM B247
		2.001-5.000	45[a]	
7050-T74	ST	0.750-6.000	35	AMS 4107
7050-T7452	ST	0.750-4.000	35	AMS 4333
7075-T73	ST	0.750-3.000	42[a]	MIL-A-22771, QQ-A-367
		3.001-4.000	41[a]	AMS-4241, ASTM B247
		4.001-5.000	39[a]	AMS 4141
		5.001-6.000	38[a]	
7075-T7352	ST	0.750-4.000	42[a]	MIL-A-22771, QQ-A-367, AMS 4147, ASTM B247
		3.001-4.000	39[a]	
7075-T7354[c]	ST	0.750-3.000	42	Company Specification
7075-T74[c]	ST	0.750-3.000	35	AMS 4131
		3.001-4.000	31[b]	
		4.001-5.000	30[b]	
		5.001-6.000	29[b]	
7149-T73	ST	0.750-2.000	46[a]	AMS 4320
		2.001-5.000	45[a]	
7175-T74	ST	0.750-3.000	35	AMS 4149, ATM B247
		3.001-4.000	31[b]	AMS 4149
		4.001-5.000	30[b]	
		5.001-6.000	29[b]	
7175-T7452[c]	ST	0.750-3.000	35	AMS 4179

[a]75% of specified minimum longitudinal yield strength.

[b]50% of specified minimum longitudinal yield strength.

[c]Design values are not included in MIL-HDBK-5.

[d]Most specifications Reference ASTM G-47, which requires 20 days of exposure for 7XXX alloys in ST test direction.

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TABLE 3.1.2.3.1(e). *Maximum Specified Tension Stress at Which Test Specimens Will Not Fail in 3½% NaCl Alternate Immersion Test[f] for Various Stress Corrosion Resistant Aluminum Hand Forgings*

Alloy and Temper	Test Direction	Thickness, inches	Stress, ksi	Referenced Specifications
7049-T73	ST	2.001-3.000	45[a]	QQ-A-367, AMS 4111, ASTM B247
		3.001-4.000	44[a]	
		4.001-5.000	42[a]	
7049-T7352[e]	ST	0.750-3.000	44[a]	AMS 4247
		3.001-4.000	43[a]	
		4.001-5.000	40[a]	
7050-T7452	ST	0.750-8.000	35	AMS 4108
7075-T73	ST	0.750-3.000	42[a]	MIL-A-22771, QQ-A-367, ASTM B247
		3.001-4.000	41[a]	
		4.001-4.000	39[a]	
		5.001-6.000	38[a]	
7075-T7352	ST	0.750-3.000	39[c]	AMS 4147
		3.001-4.000	37[c]	
		4.001-5.000	36[c]	
		5.001-6.000	34[c]	
7075-T74[e]	ST	0.750-3.000	35	AMS 4131
		3.001-4.000	30[b]	
		4.001-5.000	28[b]	
		5.001-6.000	27[b]	
7075-T7452[e]	ST	0.750-2.000	35	AMS 4323
		2.001-3.000	29[d]	
		3.001-4.000	28[d]	
		4.001-5.000	26[d]	
		5.001-6.000	24[d]	
7149-T73	ST	2.000-3.000	44[c]	AMS 4320
		3.001-4.000	43[c]	
		4.001-5.000	42[c]	
7175-T74	ST	0.750-3.000	35	AMS 4149
		3.001-4.000	29[d]	
		4.001-5.000	28[d]	
		4.001-6.000	26[d]	
7175-T7452	ST	0.750-3.000	35	AMS 4179
		3.001-4.000	27[d]	
		4.001-5.000	26[d]	
		5.001-6.000	24[d]	

[a]75% of specified minimum longitudinal yield strength.
[b]50% of specified minimum longitudinal yield strength.
[c]75% of specified minimum long transverse yield strength.
[d]50% of specified minimum long transverse yield strength.
[e]Design values are not included in MIL-HDBK-5.
[f]Most specifications Reference ASTM G-47, which requires 20 days of exposure for 7XXX alloys in ST test direction.

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alloys in certain tempers are susceptible to exfoliation corrosion, dependent upon product and section size. Generally those alloys and tempers that havethe lowest resistance to stress-corrosion cracking also have the lowest resistance to exfoliation. The tempers that provide improved resistance to stress-corrosion cracking also provide improved resistance or immunity to exfoliation. For example, the T76 temper of 7075, 7049, 7050, and 7475 provides a very high resistance to exfoliation, i.e., decidedly superior to that of the T6 temper, and almost the immunity provided by the T73 temper of 7075 alloy [see Reference 3.1.2.3.2].

3.1.3 MANUFACTURING CONSIDERATIONS

3.1.3.1 *Avoiding Stress-Corrosion Cracking.*—In order to avoid stress-corrosion cracking (see Section 3.1.2.3), practices, such as the use of press or shrink fits; taper pins; clevis joints in which tightening of the bolt imposes a bending load on female lugs; and straightening or assembly operations; which result in sustained surface tensile stresses (especially when acting in the short-transverse grain orientation), should be avoided in these high strength alloys: 2014-T451, T4, T6, T651, T652; 2024-T3, T351, T4; 7075-T6, T651, T652; 7150-T6151, T61511, and 7475-T6, T651.

Where straightening or forming is necessary it should be performed when the material is in the freshly quenched condition or at an elevated temperature to minimize the residual stress induced. Where elevated temperature forming is performed on 2014-T4 T451, or 2024-T3 T351, a subsequent precipitation heat treatment to produce the T6 or T651, T81 or T851 temper is recommended.

It is good engineering practice to control sustained short-transverse tensile stress at the surface of structural parts at the lowest practicable level. Thus, careful attention should be given in all stages of manufacturing, starting with design of the part configuration, to choose practices in the heat treatment, fabrication, and assembly to avoid unfavorable combinations of end grain microstructure and sustained tensile stress. The greatest danger arises when residual, assembly, and service stress combine to produce high sustained tensile stress at the metal surface. Sources of residual and assembly stress have been the most contributory to stress-corrosion-cracking problems because their presence and magnitude were not recognized. In most cases, the design stresses (developed by functional loads) are not continuous and would not be involved in the summation of sustained tensile stress. It is imperative that, for materials with low resistance to stress-corrosion cracking in the short-transverse grain orientation, every effort be taken to keep the level of sustained tensile stress close to zero.

3.1.3.2 *Cold-Formed Heat-Treatable Aluminum Alloys.*—Cold working such as stretch forming of aluminum alloy prior to solution heat treatment may result in recrystallization or grain growth during heat treatment. The resulting strength, particularly yield strength, may be significantly below the specified minimum values. For critical applications, the strength should be determined on the part after forming and heat treating including straightening operations. To minimize recrystallization during heat treatment it is recommended that forming be done after solution heat treatment in the as-quenched condition whenever possible, but this may result in compressive yield strength in the direction of stretching being lower than MIL-HDBK-5 design allowables for user heat treat tempers.

3.1.3.3 *Dimensional Changes.*—The dimensional changes that occur in aluminum alloy during thermal treatment generally are negligible, but in a few instances these changes may have to be considered in manufacturing. Because of many variables involved, there are no tabulated values for these dimensional changes. In the artificial aging of alloy 2219 from the T42, T351, and T37 tempers to the T62, T851, and T87 tempers, respectively, a net dimensional growth of 0.00010 to 0.0015 in./in. may be anticipated. Additional growth of as much as 0.0010 in./in. may occur during subsequent service of a year or more at 300 F or equivalent shorter exposures at higher temperatures. The dimensional changes that occur during the artificial aging of other wrought heat-treatable alloys are less that one-half that for alloy 2219 under the same conditions.

3.1.3.4 *Welding.*—The ease with which aluminum alloys may be welded is dependent principally upon composition, but the ease is also influenced by the temper of the alloy, the welding process, and the filler metal used. Also, the weldability of wrought and cast alloys is generally considered separately.

Several weldability rating systems are established and may be found in publications by the Aluminum Association, American Welding Society, and the American Society for Metals. Handbooks from these groups can be consulted for more detailed information. Specification AA-R-566 also contains much useful information. This document follows most of these references in adopting a four level rating system. An "A" level, or readily weldable, means that the alloy (and temper) is routinely welded by the indicated process using commercial procedures. A "B" level means that welding is accomplished for many applications, but special techniques are required, and the application may require preliminary trials to develop procedures and tests to demonstrate weld performance. A "C" level refers to limited weldability because crack sensitivity, loss of corrosion resistance, and/or loss of mechanical properties may occur. A "D" level indicates that the alloy is not commercially weldable.

The weldability of aluminum alloys is rated by alloy, temper, and welding process (arc or resistance). Tables 3.1.3.4(a) and (b) list the ratings in the alloy section number order in which they appear in Chapter 3.

When heat-treated or work-hardened materials of most systems are welded, a loss of mechanical properties generally occurs. The extent of the loss (if not reheat treated) over the table strength allowables will have to be established for each specific situation.

TABLE 3.1.3.4(a). *Fabrication Weldability of Wrought Aluminum Alloys*

MIL-HDBK-5 Section No.	Alloy	Tempers	Weldability[a,c]	
			Inert Gas Metal or Tungsten Arc	Resistance Spot[b]
3.2.1	2014	O	C	D
		T6, T62, T651, T652, T6510, T6511	B	B
3.2.2	2017	T4, T42, T451	C	B
3.2.3	2024	O	D	D
		T3, T351, T361, T4, T42	C	B
		T6, T62, T81, T851, T861	C	B
		T8510, T8511, T3510, T3511	C	B
3.2.4	2025	T6	C	B
3.2.5	2090	T83	B	B
3.2.6	2124	T851	C	B
3.2.7	2219	O	A	B-D
		T62, T81, T851, T87, T8510, T8511	A	A
3.2.8	2618	T61	C	B
3.2.9	2519	T87	A	...
3.5.1	5052	O	A	B
		H32, H34, H36, H38	A	A
3.5.2	5083	O	A	B
		H321, H323, H343, H111, H112	A	A
3.5.3	5086	O	A	B
		H32, H34, H36, H38, H111, H112	A	A
3.5.4	5454	O	A	B
		H32, H32, H111, H112	A	A
3.5.5	5456	O	A	B
		H111, H321, H112	A	A
3.6.1	6013	T6	A	A
3.6.2	6061	O	A	B
		T4, T42, T451, T4510, T4511, T6	A	A
		T62, T651, T652, T6510, T6511	A	A
3.6.3	6151	T6	A	A
3.7.1	7010	All	C	B
3.7.2	7049 7149	All	C	B
3.7.3	7050	All	C	B
3.7.4	7075	All	C	B
3.7.5	7150	All	C	B
3.7.6	7175	All	C	B
3.7.7	7475	All	C	B

[a]Ratings A through D are relative ratings defined as follows:
A - Generally weldable by all commercial procedures and methods.
B - Weldable with special techniques or for specific applications which justify preliminary trials or testing to develop welding procedures and weld performance.
C - Limited weldability because of crack sensitivity or loss in resistance to corrosion and mechanical properties.
D - No commonly used welding methods have been developed.
[b]See MIL-W-6858 for permissible combinations.
[c]When using filler wire, the wire should contain less than 0.0008 percent beryllium to avoid toxic fumes.

TABLE 3.1.3.4(b). *Fabrication Weldability[a] of Cast Aluminum Alloys*

MIL-HDBK-5 Section No.	Alloy	Weldability[b,c]	
		Inert Gas Metal or Tungsten Arc	Resistance Spot
3.8.1	A201.0	C	C
3.9.1	354.0	B	B
3.9.2	355.0	B	B
3.9.3	C355.0	B	B
3.9.4	356.0	A	A
3.9.5	A356.0	A	A
3.9.6	A357.0	A	B
3.9.7	D357.0	A	A
3.9.8	359.0	A	B

[a]Weldability related to joining a casting to another part of same composition. The weldability ratings are not applicable to minor weld repairs. Such repairs shall be governed by the contractors procedure for in-process welding of castings, after approval by the procuring activity.

[b]Ratings A through D are relative ratings defined as follows:

A - Generally weldable by all commercial procedures and methods.

B - Weldable with special techniques or for specific applications which justify preliminary trials or testing to develop welding procedure and weld performance.

C - Limited weldability because of crack sensitivity or loss in resistance to corrosion and mechanical properties.

D - No commonly used welding methods have been developed.

[c]When using filler wire, the wire should contain less than 0.0008 percent beryllium to avoid toxic fumes.

3.2 2000 Series Wrought Alloys

Alloys of the 2000 series contain copper as the principal alloying element and are strengthened by solution heat treatment and aging. As a group, these alloys are noteworthy for their excellent strengths at elevated and cryogenic temperatures, and creep resistance at elevated temperatures.

3.2.1 2014 ALLOY

3.1.2.0 *Comments and Properties.*—2014 is an Al-Cu alloy available in a wide variety of product forms. Refer to Section 3.1.2.3 for comments regarding the resistance of the alloy to stress-corrosion cracking, and to Section 3.1.3.4 for comments regarding the weldability of the alloy.

Material specifications for 2014 aluminum alloy are presented in Table 3.2.1.0(a). Room-temperature mechanical and physical properties are shown in Tables 3.2.1.0(b) through (g). Figure 3.2.1.0 shows the effect of temperature on the physical properties of 2014 alloy.

TABLE 3.2.1.0(a). *Material Specifications for 2014 Aluminum Alloy*

Specification	Form
AMS 4028	Bare sheet and plate
AMS 4029	Bare sheet and plate
QQ-A-250/3	Clad sheet and plate
QQ-A-225/4	Rolled or drawn bar, rod, and shapes
AMS 4121	Bar and rod, rolled or cold finished
QQ-A-200/2	Extruded bar, rod, and shapes
AMS 4153	Extrusion
MIL-A-22771	Forging
QQ-A-367	Forging
AMS 4133	Forging

The temper index for 2014 is as follows:

Section	Temper
3.2.1.1	T6, T62, T651, T652, T6510, and T6511

3.2.1.1 *T6, T62, T651, T652, T6510, and T6511 Temper.*—Figures 3.2.1.1.1(a) through 3.2.1.1.5(b) present elevated-temperature curves for various mechanical properties. Figures 3.2.1.1.6(a) through (r) present tensile and compressive stress-strain and tangent-modulus curves for various tempers, product forms, and temperatures. Figures 3.2.1.1.6(s) through (v) are full-range tensile stress-strain curves for various products and tempers. Figures 3.2.1.1.8(a) through (e) contain S/N fatigue curves for various wrought products in the T6 temper.

TABLE 3.2.1.0(b$_1$). *Design Mechanical and Physical Properties of 2014 Aluminum Alloy Sheet and Plate*

Specification	AMS 4029															
Form	Sheet				Plate											
Temper	T6				T651[a]											
Thickness, in.	0.020-0.039		0.040-0.249		0.250-0.499		0.500-1.000		1.001-2.000		2.001-2.500		2.501-3.000		3.001-4.000	
Basis	A	B	A	B	A	B	A	B	A	B	A	B	A	B	A	B
Mechanical Properties:																
F_{tu}, ksi:																
L	65	67	67	68	66	68	66	67	66	67	64	65	...	...	...	...
LT	64	66	66	67	67	69	67	68	67	68	65	66	63	64	59	60
ST	...	...	...	...	...	...	...	...	...	...	59	60	...	...	...	...
F_{ty}, ksi:																
L	58	60	59	60	60	62	60	61	60	62	59	61	...	...	...	...
LT	57	59	58	59	59	61	59	60	59	61	58	60	57	59	55	57
ST	...	...	...	...	...	...	...	...	...	...	54	56	...	...	...	...
F_{cy}, ksi:																
L	58	60	59	60	58	60	58	59	58	60	57	59	...	...	...	...
LT	59	61	60	61	61	63	61	62	61	63	60	62	...	...	...	...
ST	...	...	...	...	...	...	...	...	...	...	59	61	...	...	...	...
F_{su}, ksi	39	40	40	41	40	41	40	41	40	41	38	39	...	...	...	...
F_{bru}, ksi:																
(e/D = 1.5)	97	100	100	102	105	108	105	107	105	107	102	104	...	...	...	...
(e/D = 2.0)	123	127	127	129	134	138	134	136	134	136	130	132	...	...	...	...
F_{bry}, ksi:																
(e/D = 1.5)	81	84	83	84	90	93	90	92	90	93	88	92	...	...	...	...
(e/D = 2.0)	93	96	94	96	106	110	106	109	106	110	104	109	...	...	...	...
e, percent (S-basis):																
LT	6	...	7	...	7	...	6	...	4	...	2	...	2	...	1	...
E, 10^3 ksi	10.5				10.7											
E_c, 10^3 ksi	10.7				10.9											
G, 10^3 ksi	4.0				4.0											
μ	0.33				0.33											
Physical Properties:																
ω, lb/in.^{3}	0.101															
C, K, and α	See Figure 3.2.1.0															

[a]Bearing values are "dry pin" values per Section 1.4.7.1. See Table 3.1.2.1.1.

TABLE 3.2.1.0(b$_2$). *Design Mechanical and Physical Properties of 2014 Aluminum Alloy Sheet and Plate—Continued*

Specification	AMS 4028							
Form	Sheet				Plate[a]			
Temper	T62[b]							
Thickness, in.	0.020-0.039		0.040-0.249		0.250-0.499		0.500-1.000	
Basis	A	B	A	B	A	B	A	B
Mechanical Properties:								
F_{tu}, ksi:								
L	65	67	67	68	65	67	65	67
LT	64	66	66	67	67	69	67	69
F_{ty}, ksi:								
L	58	60	59	60	57	59	57	59
LT	57	59	58	59	59	61	59	61
F_{cy}, ksi:								
L	58	60	59	60	59	61	59	61
LT	59	61	60	61	60	62	60	62
F_{su}, ksi	39	40	40	41	37	39	37	39
F_{bru}, ksi:								
(e/D = 1.5)	97	100	100	102	100	103	100	103
(e/D = 2.0)	123	127	127	129	127	131	127	131
F_{bry}, ksi:								
(e/D = 1.5)	81	84	83	84	84	87	84	87
(e/D = 2.0)	93	96	95	96	99	103	99	103
e, percent (S-basis):								
LT	6	...	7	...	7	...	6	...
E, 10^3 ksi	10.5				10.7			
E_c, 10^3 ksi	10.7				10.9			
G, 10^3 ksi	4.0				4.0			
μ	0.33				0.33			
Physical Properties:								
ω, lb/in.^{3}	0.101							
C, K, and α	See Figure 3.2.1.0							

[a] Bearing values are "dry pin" values per Section 1.4.7.1.

[b] Design allowables were based upon data obtained from testing samples of material, supplied in the O or F temper, which were heat treated to demonstrate response to heat treatment by suppliers. Properties obtained by the user may be lower than those listed if the material has been formed or otherwise cold or hot worked, particularly in the annealed temper, prior to solution heat treatment.

TABLE 3.2.1.0(c_1). *Design Mechanical and Physical Properties of Clad 2014 Aluminum Alloy Sheet and Plate*

Specification	QQ-A-250/3															
Form	Sheet				Plate											
Temper	T6				T651[a]											
Thickness, in.	0.020-0.039		0.040-0.249		0.250-0.499		0.500-1.000[b]		1.001-2.000[b]		2.001-2.500[b]		2.501-3.000[b]		3.001-4.000[b]	
Basis	A	B	A	B	A	B	A	B	A	B	A	B	A	B	A	B
Mechanical Properties:																
F_{tu}, ksi:																
L	62	64	65	67	63	65	63	64	63	64	61	62	...	...	...	...
LT	61	63	64	66	64	66	64	65	64	65	62	63	60	61	56	57
ST	...	...	...	...	...	...	...	...	...	...	59	60	...	...	...	...
F_{ty}, ksi:																
L	54	56	57	59	58	60	57	58	57	59	56	58	...	...	...	...
LT	53	55	56	58	57	59	56	57	56	58	55	57	54	56	52	54
ST	...	...	...	...	...	...	...	...	...	...	54	56	...	...	...	...
F_{cy}, ksi:																
L	54	56	57	59	56	58	55	56	55	57	54	56	...	...	...	...
LT	55	57	58	60	59	61	58	59	58	60	57	59	...	...	...	...
ST	...	...	...	...	...	...	...	...	...	...	59	61	...	...	...	...
F_{su}, ksi	37	38	39	40	38	39	38	38	38	38	37	37	...	...	...	...
F_{bru}, ksi:																
(e/D = 1.5)	93	96	97	100	101	104	101	102	101	102	97	99	...	...	...	...
(e/D = 2.0)	117	121	123	127	128	132	128	130	128	130	124	126	...	...	...	...
F_{bry}, ksi:																
(e/D = 1.5)	76	78	80	83	87	90	85	87	85	88	84	87	...	...	...	...
(e/D = 2.0)	86	89	91	94	102	106	100	102	100	104	98	102	...	...	...	...
e, percent (S-basis):																
LT	7	...	8	...	8	...	6	...	4	...	2	...	2	...	1	...
E, 10^3 ksi	10.5				10.7											
E_c, 10^3 ksi	10.7				10.9											
G, 10^3 ksi	4.0				4.0											
μ	0.33				0.33											
Physical Properties:																
ω, lb/in.^{3}	0.101															
C, K, and α	...															

[a]Bearing values are "dry pin" values per Section 1.4.7.1. See Table 3.1.2.1.1.
[b]These values, except in the ST direction, have been adjusted to represent the average properties across the whole section, including the 2-½ percent per side nominal cladding thickness.

TABLE 3.2.1.0(c_2). *Design Mechanical and Physical Properties of Clad 2014 Aluminum Alloy Sheet and Plate—Continued*

Specification	QQ-A-250/3									
Form	Sheet				Plate[a]					
Temper	T62[b]									
Thickness, in.	0.020-0.039		0.040-0.249		0.250-0.499	0.500-1.000[c]	1.001-2.000[c]	2.001-2.500[c]	2.501-3.000[c]	3.001-4.000[c]
Basis	A	B	A	B	S	S	S	S	S	S
Mechanical Properties:										
F_{tu}, ksi:										
L	62	64	65	67	62	62	62	60	...	...
LT	61	63	64	66	64	64	64	62	60	56
F_{ty}, ksi:										
L	54	56	57	59	55	54	54	53	...	...
LT	53	55	56	58	57	56	56	55	54	52
F_{cy}, ksi:										
L	54	56	57	59	57	56	56	55	...	...
LT	55	57	58	60	58	57	56	55	...	...
F_{su}, ksi	37	38	39	40	36	36	36	35	...	...
F_{bru}, ksi:										
(e/D = 1.5)	93	96	97	100	96	96	96	93	...	...
(e/D = 2.0)	117	121	123	127	121	121	121	118	...	...
F_{bry}, ksi:										
(e/D = 1.5)	76	78	80	83	81	79	79	78	...	...
(e/D = 2.0)	86	89	91	94	96	94	94	92	...	...
e, percent (S-basis):										
LT	7	...	8	...	8	6	4	2	2	1
E, 10^3 ksi	10.5				10.7					
E_c, 10^3 ksi	10.7				10.9					
G, 10^3 ksi	4.0				4.0					
μ	0.33				0.33					
Physical Properties:										
ω, lb/in.^{3}	0.101									
C, K, and α	...									

[a]Bearing values are "dry pin" values per Section 1.4.7.1. See Table 3.1.2.1.1.

[b]Design allowables were based upon data obtained from testing samples of material, supplied in the O or F temper, which were heat treated to demonstrate response to heat treatment by suppliers. Properties obtained by the user may be lower than those listed if the material has been formed or otherwise cold or hot worked, particularly in the annealed temper, prior to solution heat treatment.

[c]These values have been adjusted to represent the average properties across the whole section, including the 2-½ percent per side nominal cladding thickness.

TABLE 3.2.1.0(d). *Design Mechanical and Physical Properties of 2014 Aluminum Alloy Bar, Rod, and Shapes; Rolled, Drawn, or Cold-Finished*

Specification	AMS 4121 and QQ-A-225/4							QQ-A-225/4
Form	Bar, rod, and shapes, rolled, drawn, or cold-finished							
Temper	T6 and T651							T62[a]
Thickness, in.	Up to 1.000	1.001-2.000	2.001-3.000	3.001-4.000	4.001-5.000[b]	5.001-6.000[b]	6.001-8.000[b]	≤8.000[b]
Basis	S	S	S	S	S	S	S	S
Mechanical Properties:								
F_{tu}, ksi:								
L	65	65	65	65	65	65	65	65
LT	64	63	62	61	60	59	...	...
F_{ty}, ksi:								
L	55	55	55	55	55	55	55	55
LT	53	52	51	50	49	48	...	...
F_{cy}, ksi:								
L	53	53	53	53	53	53	53	...
LT	...	...	...	...	...	...	...	...
F_{su}, ksi	38	38	38	38	38	38	38	...
F_{bru}, ksi:								
(e/D = 1.5)	98	...	...	...	...	...	...	...
(e/D = 2.0)	124	...	...	...	...	...	...	...
F_{bry}, ksi:								
(e/D = 1.5)	77	...	...	...	...	...	...	...
(e/D = 2.0)	88	...	...	...	...	...	...	...
e, percent:								
L	8	8	8	8	8	8	8	8
E, 10^3 ksi	10.5							
E_c, 10^3 ksi	10.7							
G, 10^3 ksi	4.0							
μ	0.33							
Physical Properties:								
ω, lb/in.^{3}	0.101							
C, K, and α	See Figure 3.2.1.0							

[a]Design allowables were based upon data obtained from testing samples of material, supplied in the O or F temper, which were heat treated to demonstrate response to heat treatment by suppliers.
[b]For square, rectangular, hexagonal, or octagonal bar, maximum thickness is 4 in., and maximum cross-sectional area is 36 sq. in.

TABLE 3.2.1.0(e). *Design Mechanical and Physical Properties of 2014 Aluminum Alloy Die Forging*

Specification	AMS 4133, MIL-A-22771, and QQ-A-367							MIL-A-22771 and QQ-A-367						
Form	Die forging													
Temper	T6[c]							T652						
Thickness[e], in.	≤ 1.000		1.001-2.000		2.001-3.000		3.001-4.000	≤ 1.000		1.001-2.000		2.001-3.000		3.001-4.000
Basis	A	B	A	B	A	B	S	A	B	A	B	A	B	S
Mechanical Properties:														
F_{tu}, ksi:														
L	65	67	65	67	65	67	63	65	67	65	67	65	67	63
T[a]	64[d]	...	64[d]	...	63[d]	...	63	64[d]	...	64[d]	...	63[d]	...	63
F_{ty}, ksi:														
L	56	59	56	59	55	58	55	56	59	56	59	55	58	55
T[a]	55[d]	...	55[d]	...	54[d]	...	54	55[d]	...	55[d]	...	54[d]	...	54
F_{cy}, ksi:														
L	59	62	59	62	58	61	58	56	59	56	59	55	58	55
ST	56	59	56	59	55	58	55	59	62	59	62	58	61	58
F_{su}, ksi	40	41	40	41	39	40	39	40	41	40	41	39	40	39
F_{bru}[b], ksi:														
(e/D = 1.5)	91	94	91	94	91	94	88	91	94	91	94	91	94	88
(e/D = 2.0)	123	127	123	127	123	127	120	123	127	123	127	123	127	120
F_{bry}[b], ksi:														
(e/D = 1.5)	73	77	73	77	71	75	71	73	77	73	77	71	75	71
(e/D = 2.0)	90	94	90	94	88	93	88	90	94	90	94	88	93	88
e, percent (S-basis):														
L	6	...	6	...	6	...	6	6	...	6	...	6	...	6
T[a]	3	...	2	...	2	...	2	3	...	2	...	2	...	2
E, 10^3 ksi	10.5													
E_c, 10^3 ksi	10.8													
G, 10^3 ksi	4.0													
μ	0.33													
Physical Properties:														
ω, lb/in.^{3}	0.101													
C, K, and α	See Figure 3.2.1.0													

[a] For die forgings, T indicates any grain direction not within ±15° of being parallel to the forging flow lines. Specimens to test transverse properties should be located as close to the short transverse direction as possible.
[b] Bearing values are "dry pin" values per Section 1.4.7.1.
[c] When die forgings are machined before heat treatment, the mechanical properties are applicable, provided the as-forged thickness is not greater than twice the thickness at the time of heat treatment.
[d] Specification value. T tensile properties are presented on S basis only.
[e] Thickness at time of heat treatment.

TABLE 3.2.1.0(f). *Design Mechanical and Physical Properties of 2014 Aluminum Alloy Hand Forging*

Specification	AMS 4133, MIL-A-2271, and QQ-A-367							MIL-A-2271 and QQ-A-367						
Form	Hand forging													
Temper	T6[a]							T652[b]						
Cross-sectional area, in.^{2}	≤ 256													
Thickness, in.	≤2.000	2.001-3.000	3.001-4.000	4.001-5.000	5.001-6.000	6.001-7.000	7.001-8.000	≤2.000	2.001-3.000	3.001-4.000	4.001-5.000	5.001-6.000	6.001-7.000	7.001-8.000
Basis	S	S	S	S	S	S	S	S	S	S	S	S	S	S
Mechanical Properties:														
F_{tu}, ksi:														
L	65	64	63	62	61	60	59	65	64	63	62	61	60	59
LT	65	64	63	62	61	60	59	65	64	63	62	61	60	59
ST	...	62	61	60	59	58	57	...	62	61	60	59	58	57
F_{ty}, ksi:														
L	56	56	55	54	53	52	51	56	56	55	54	53	52	51
LT	56	55	55	54	53	52	51	56	55	55	54	53	52	51
ST	...	55	54	53	53	52	51	...	52	51	50	50	49	48
F_{cy}, ksi:														
L	56	56	55	54	53	...	...	56	56	55	54	53	...	...
LT	56	55	55	54	53	...	...	57	56	56	53	54	...	...
ST	...	...	...	...	...	...	...	...	57	56	55	55	...	...
F_{su}, ksi	40	39	39	38	38	...	...	38	37	37	36	36	...	...
F_{bru}, ksi:														
(e/D = 1.5)	91	90	88	87	85	...	...	88	87	85	84	83	...	...
(e/D = 2.0)	117	115	113	112	110	...	...	115	113	111	110	108	...	...
F_{bry}, ksi:														
(e/D = 1.5)	78	78	77	76	74	...	...	77	76	76	74	73	...	...
(e/D = 2.0)	90	90	88	87	85	...	...	91	89	89	87	86	...	...
e, percent:														
L	8	8	8	7	7	6	6	8	8	8	7	7	6	6
LT	3	3	3	2	2	2	2	3	3	3	2	2	2	2
ST	...	2	2	1	1	1	1	...	2	2	1	1	1	1
E, 10^3 ksi	10.5													
E_c, 10^3 ksi	10.8													
G, 10^3 ksi	4.0													
μ	0.33													
Physical Properties:														
ω, lb/in.^{3}	0.101													
C, K, and α	See Figure 3.2.1.0													

[a]When hand forgings are machined before heat treatment, the section thickness at time of heat treatment shall determine the minimum mechanical properties as long as the original (as-forged) thickness does not exceed the maximum thickness for the alloy as shown in the table.
[b]Bearing values are "dry pin" values per Section 1.4.7.1.

TABLE 3.2.1.0(g). *Design Mechanical and Physical Properties of 2014 Aluminum Alloy Extrusion*

Specification	AMS 4153 and QQ-A-200/2										QQ-A-200/2			
Form	Extruded bar, rod, and shapes													
Temper	T6, T6510, and T6511										T62[a]			
Cross-sectional area, in.^{2}	≤25									>25-≤32	All	≤25	>25-≤32
Thickness or dia., in.[b]	0.125-0.499		0.500-0.749		0.750-1.499		1.500-1.750		1.751-2.999	3.000-4.499	≥0.750	≤0.749	≥0.750	≥0.750
Basis	A	B	A	B	A	B	A	B	S	S	S	S	S	S
Mechanical Properties:														
F_{tu}, ksi:														
L	60	62	64	68	68	70	68	71	68	68	68	60	60	60
LT	60[e]	...	64[e]	...	63[e]	...	61[e]	...	61	58	56	...	...	...
F_{ty}, ksi:														
L	53	57	58	62	60	63	60	63	60	60	58	53	53	53
LT	53[e]	...	55[e]	...	54[e]	...	52[e]	...	52	49	47	...	...	...
F_{cy}, ksi:														
L	52	56	57	61	59	62	59	62	...	...	...	...	...	...
LT	...	...	...	...	...	...	...	...	...	...	...	...	...	...
F_{su}, ksi	35	36	37	39	39	41	39	41	...	...	...	...	...	...
F_{bru}[c], ksi:														
(e/D = 1.5)	90	93	96	102	102	105	102	106	...	...	...	...	...	...
(e/D = 2.0)	116	120	124	132	132	136	132	138	...	...	...	...	...	...
F_{bry}[c], ksi:														
(e/D = 1.5)	73	78	80	85	82	86	82	86	...	...	...	...	...	...
(e/D = 2.0)	85	91	93	99	96	101	96	101	...	...	...	...	...	...
e, percent (S-basis):														
L	7	...	7	...	7	...	7	...	7	7	6	7	7	6
LT	5[d]	...	5	...	2	...	2	...	2	1	1	...	...	...
E, 10^3 ksi	10.8													
E_c, 10^3 ksi	11.0													
G, 10^3 ksi	4.1													
μ	0.33													
Physical Properties:														
ω, lb/in.^{3}	0.101													
C, K, and α	See Figure 3.2.1.0													

[a] Design allowables were based upon data obtained from testing samples of material, supplied in O or F temper, which were heat treated to demonstrate response to heat treatment by suppliers.
[b] For extrusion with outstanding legs, the load-carrying ability of such legs shall be determined on the basis of the properties in the appropriate column corresponding to the leg thickness.
[c] Bearing values are "dry pin" values per Section 1.4.7.1.
[d] For 0.375-0.499 in.
[e] S-basis.

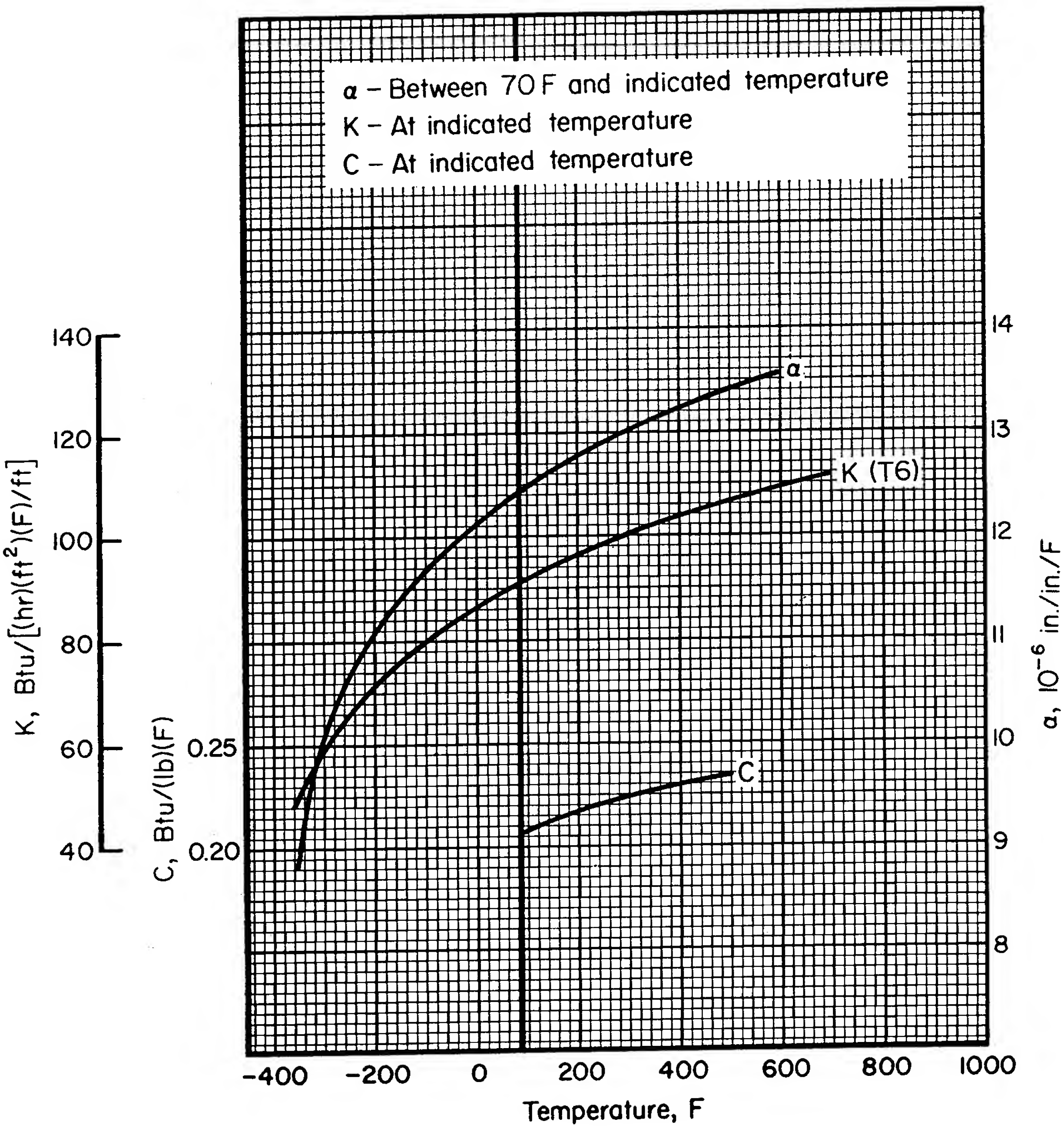

FIGURE 3.2.1.0. *Effect of temperature on the physical properties of 2014 aluminum alloy.*

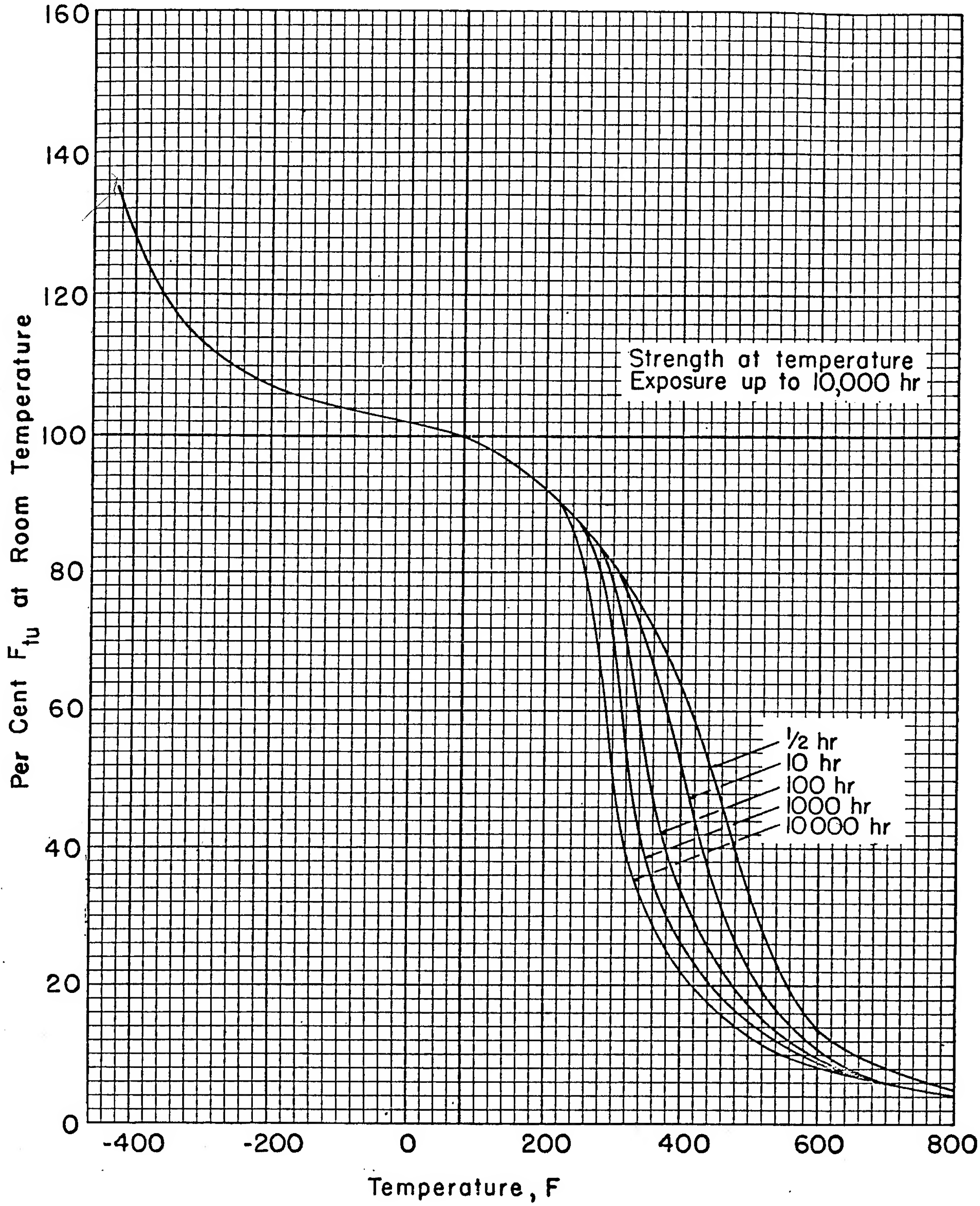

FIGURE 3.2.1.1.1(a). *Effect of temperature on the ultimate tensile strength (F_{tu}) of 2014-T6, T651, T6510 and T6511 aluminum alloy (bare and clad sheet and plate 0.040-1.500 in. thick; extruded bar, rod and shapes $\leq$ 0.750 in. thick with cross-sectional area $\leq$ 32 sq. in.).*

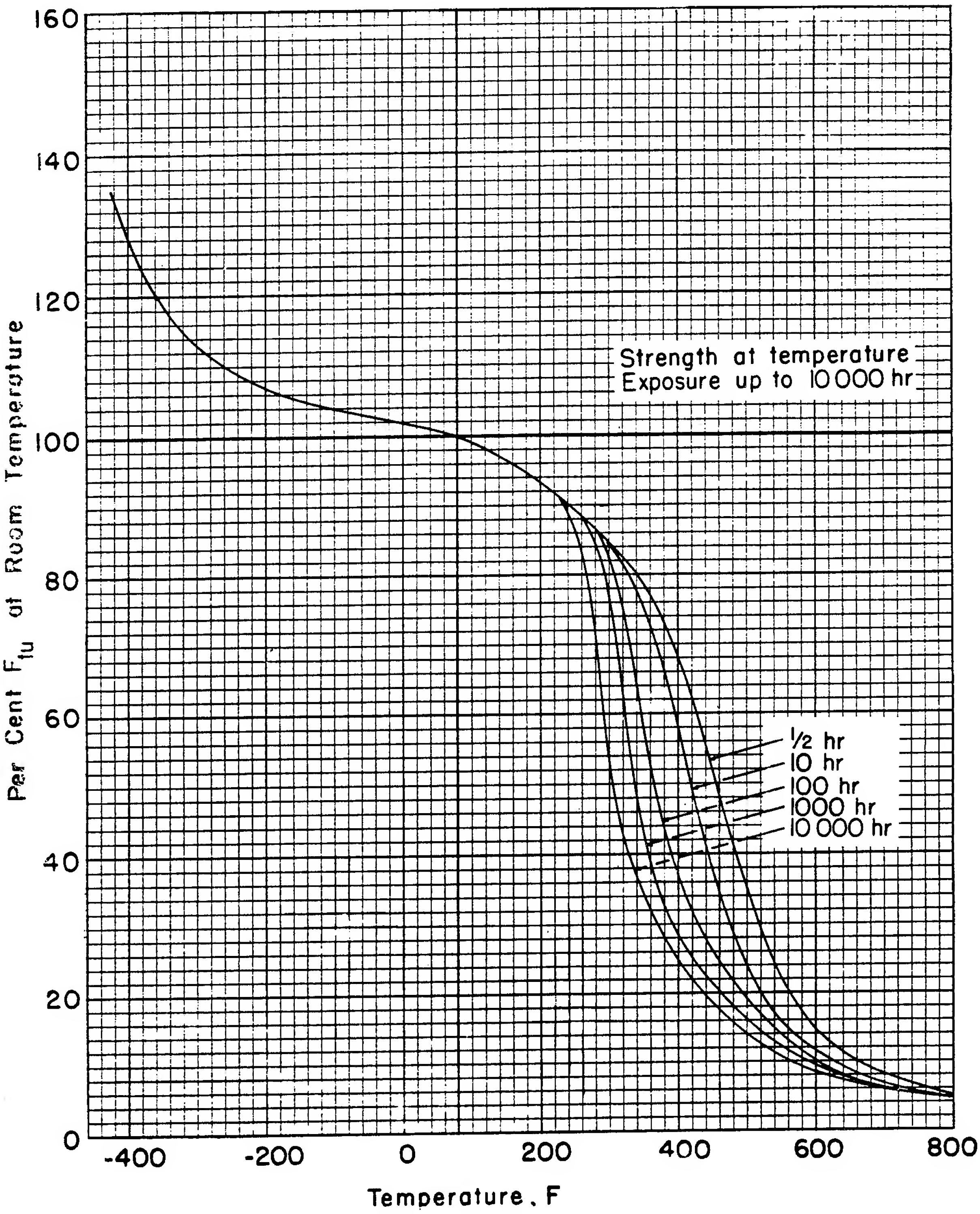

FIGURE 3.2.1.1.1(b). *Effect of temperature on the ultimate strength (F_{tu}) of 2014-T6, T651, T6510 and T6511 aluminum alloy (bare and clad sheet 0.020-0.039 in. thick; bare and clad plate 1.501-4.000 in. thick; rolled bar, rod and shapes; hand and die forgings; extruded bar, rod and shapes 0.125-0.749 in. thick with cross-sectional area ≤ 25 sq. in.).*

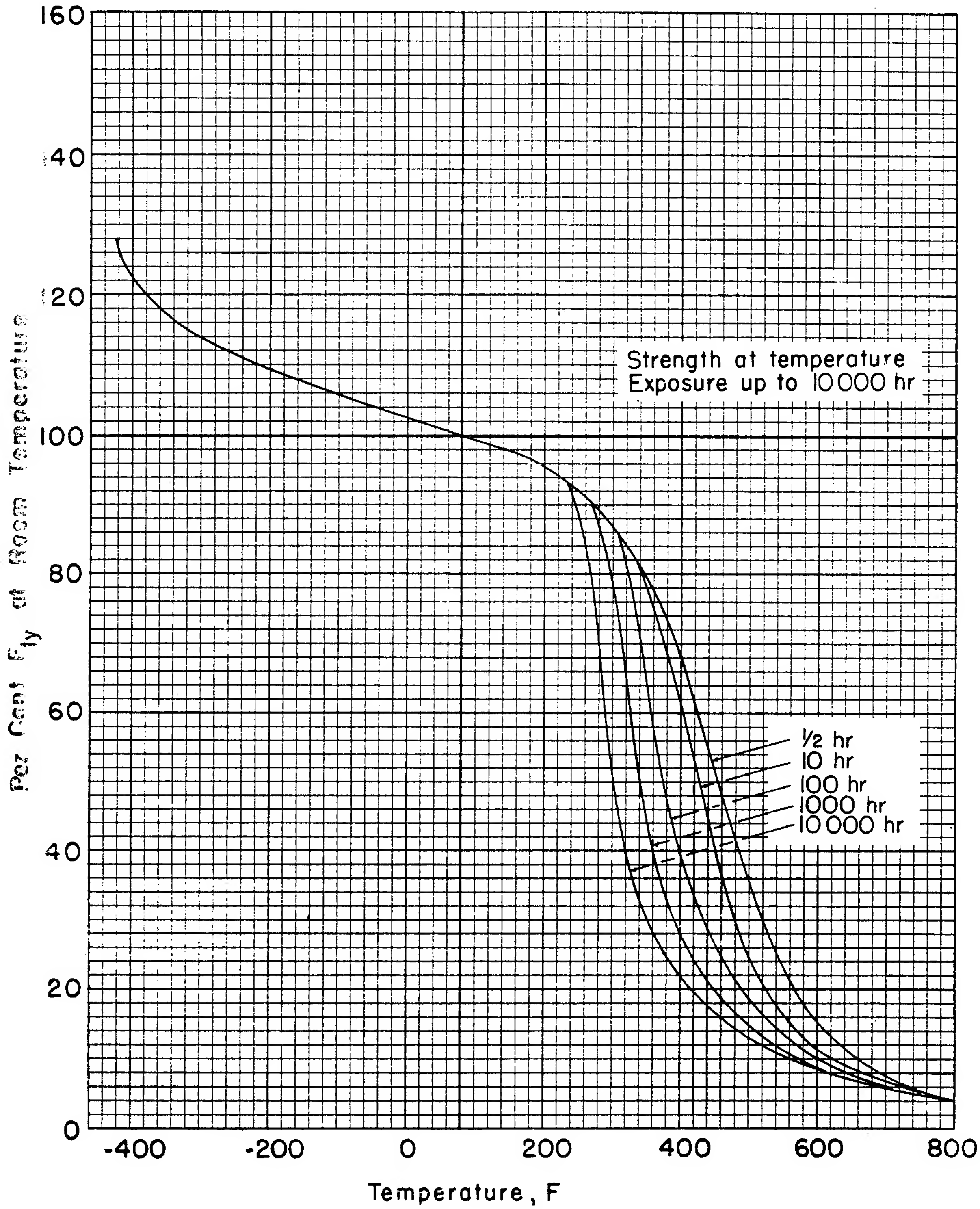

FIGURE 3.2.1.1.1(c). *Effect of temperature on the tensile yield strength (F_{ty}) of 2014-T6, T651, T6510 and T6511 aluminum alloy (bare and clad plate 3.001-4.000 in. thick; rolled bar, rod and shapes; hand and die forgings; extruded bar, rod and shapes 0.125-0.499 in. thick with cross-sectional area ≤25 sq. in.).*

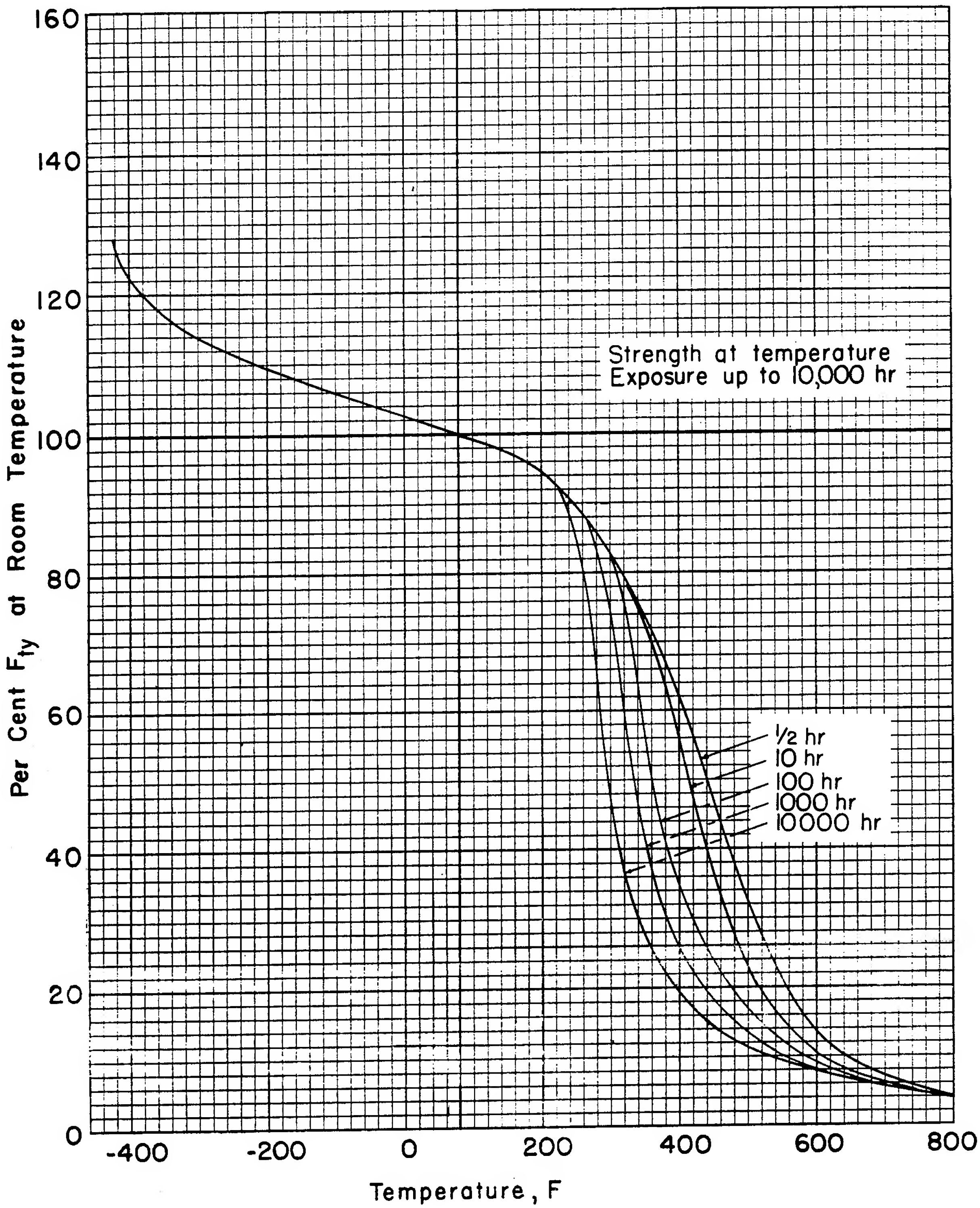

FIGURE 3.2.1.1.1(d). *Effect of temperature on the tensile yield strength (F_{ty}) of 2014-T6, T651, T6510, and T6511 aluminum alloy (bare and clad sheet and plate 0.020-3.000 in. thick; extruded bar, rod and shapes 0.500-0.749 in. thick with cross-sectional area ≤ 25 sq in., and ≥ 0.750 in. thick with cross-sectional area ≤ 32 sq in.).*

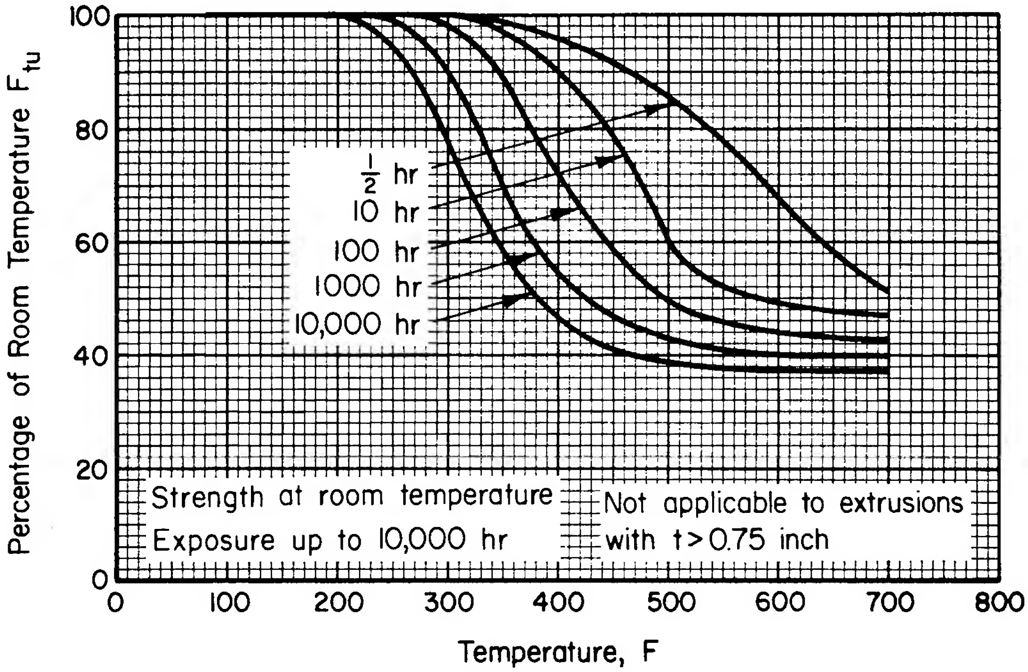

FIGURE 3.2.1.1.1(e). *Effect of exposure at elevated temperatures on the room-temperature tensile ultimate strength (F_{tu}) of 2014-T6, T651, T6510, and T6511 aluminum alloy (all products except thick extrusions).*

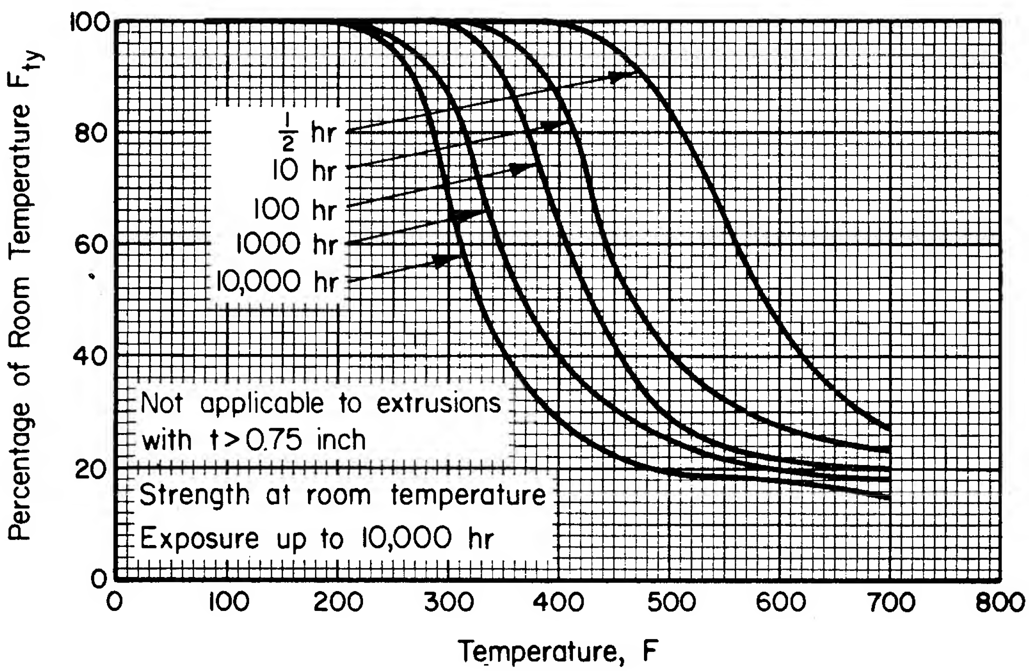

FIGURE 3.2.1.1.1(f). *Effect of exposure at elevated temperature on the room-temperature tensile yield strength (F_{ty}) of 2014-T6, T651, T6510 and T6511 aluminum alloy (all products except thick extrusions.*

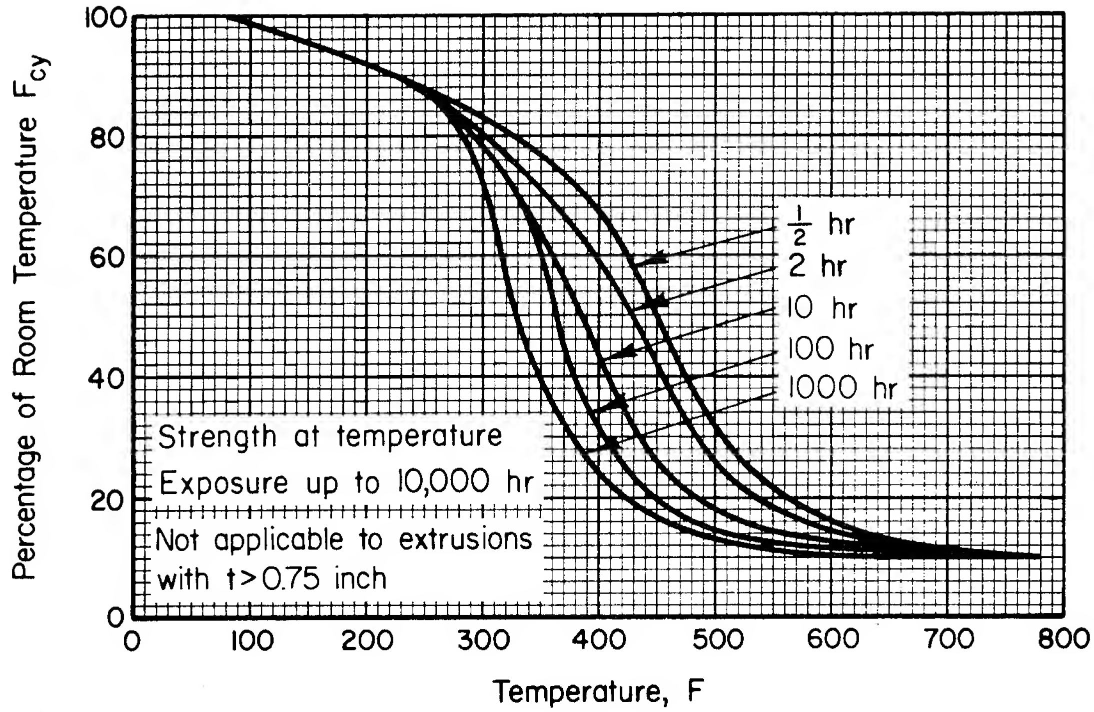

FIGURE 3.2.1.1.2(a). *Effect of temperature on the compressive yield strength (F_{cy}) of 2014-T6, T651, T6510 and T6511 aluminum alloy (all products except thick extrusions).*

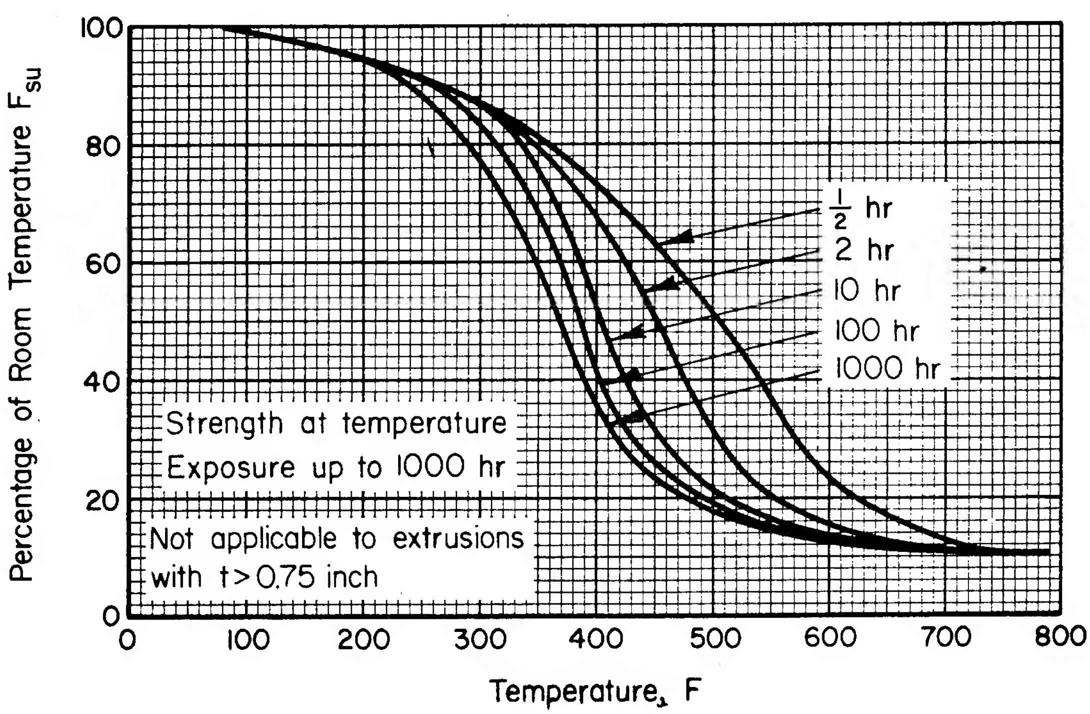

FIGURE 3.2.1.1.2(b). *Effect of temperature on the shear ultimate strength (F_{su}) of 2014-T6, T651, T6510 and T6511 aluminum alloy (all products except thick extrusions).*

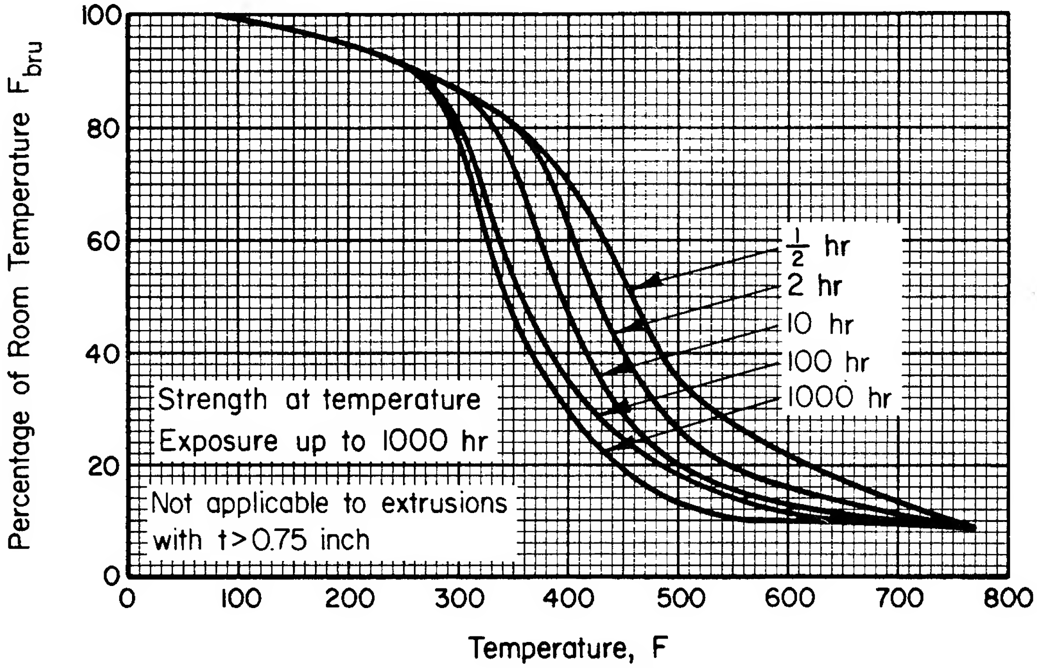

FIGURE 3.2.1.1.3(a). *Effect of temperature on the bearing ultimate strength (F_{bru}) of 2014-T6, T651, T6510 and T6511 aluminum alloy (all products except thick extrusions).*

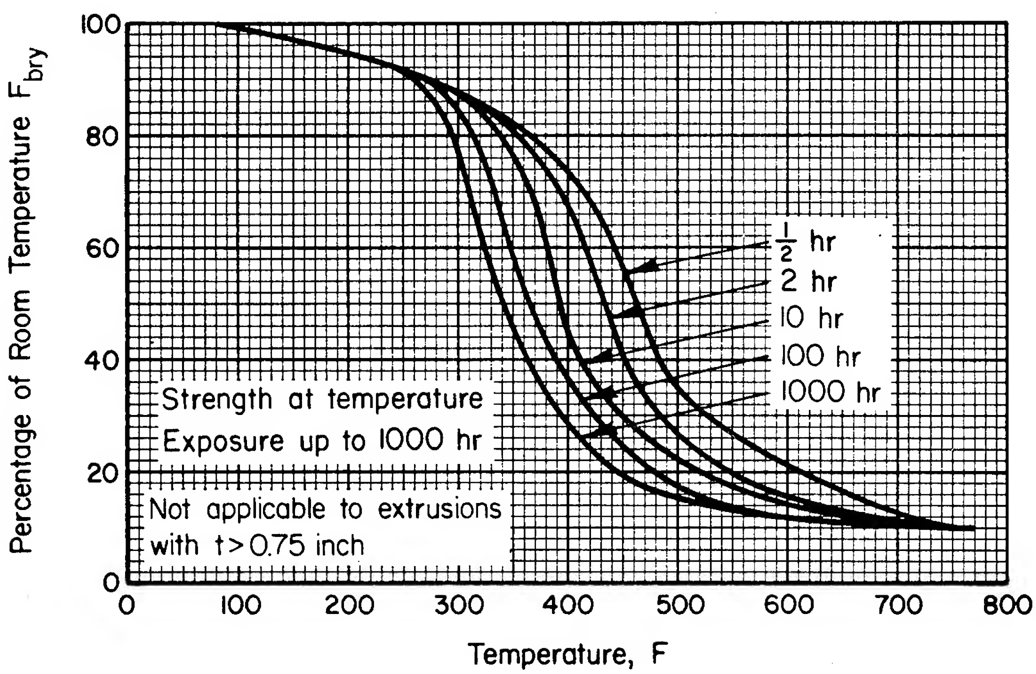

FIGURE 3.2.1.1.3(b). *Effect of temperature on the bearing yield strength (F_{bry}) of 2014-T6, T651, T6510 and T6511 aluminum alloy (all products except thick extrusions).*

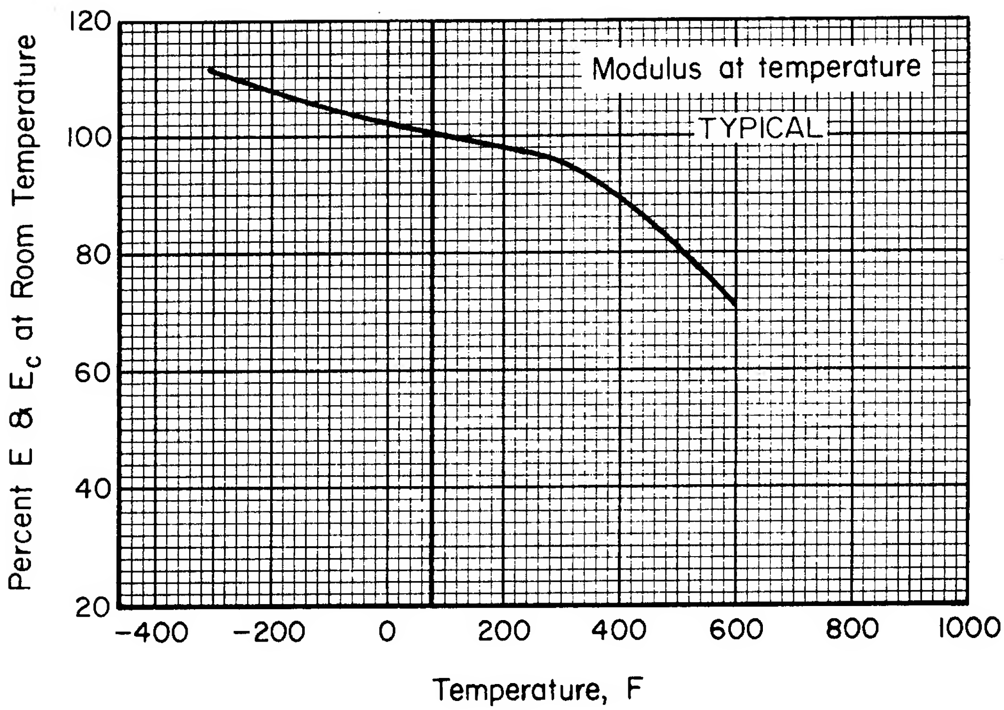

FIGURE 3.2.1.1.4. *Effect of temperature on the tensile and compressive moduli (E and E_c) of 2014 aluminum alloy.*

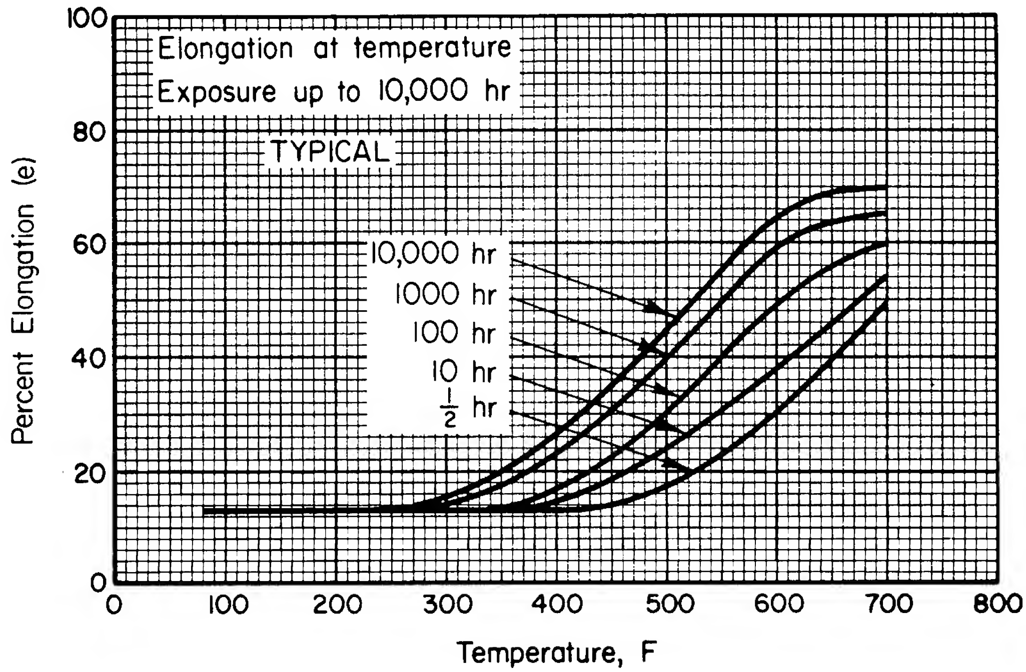

FIGURE 3.2.1.1.5(a). *Effect of temperature on the elongation of 2014-T6, T651, T6510 and T6511 aluminum alloy (all products except thick extrusions).*

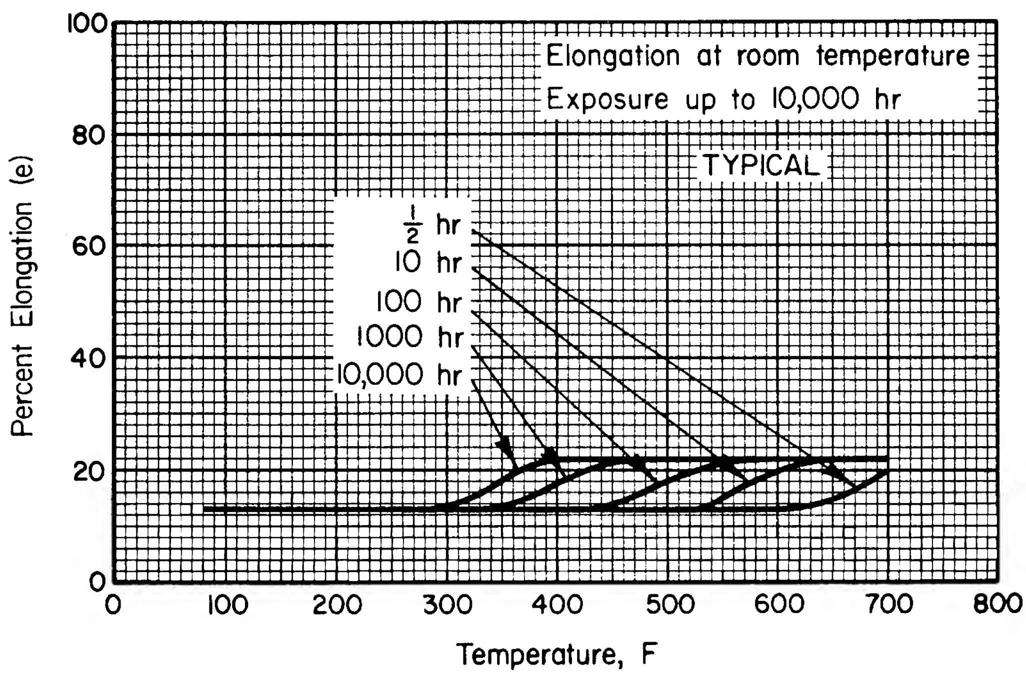

FIGURE 3.2.1.1.5(b). *Effect of exposure at elevated temperatures on the room-temperature elongation of 2014-T6, T651, T6510 and T6511 aluminum alloy (all products except thick extrusions).*

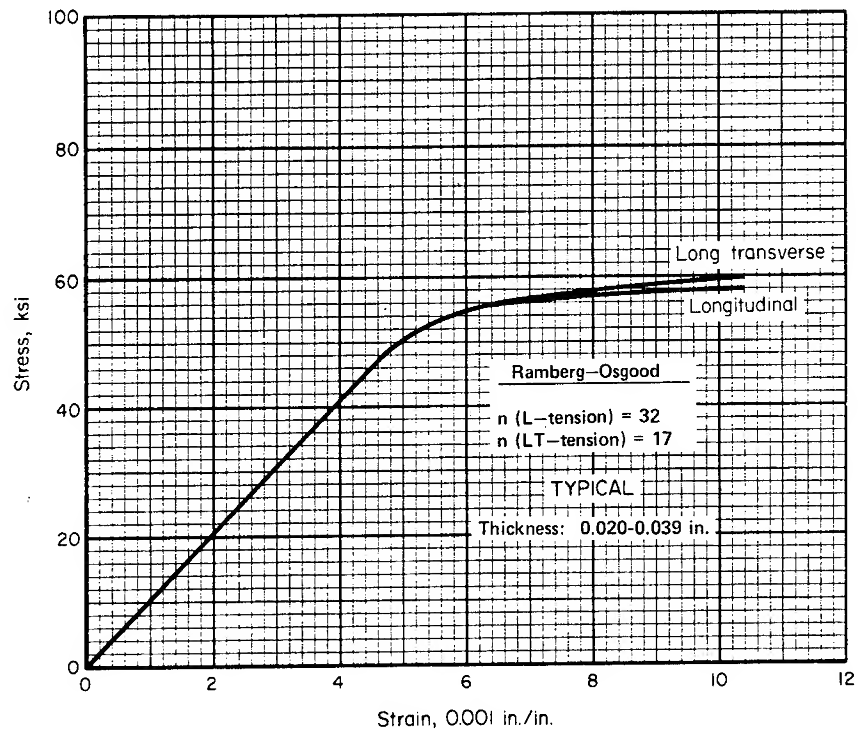

FIGURE 3.2.1.1.6(a). *Typical tensile stress-strain curves for clad 2014-T6 aluminum alloy sheet at room temperature.*

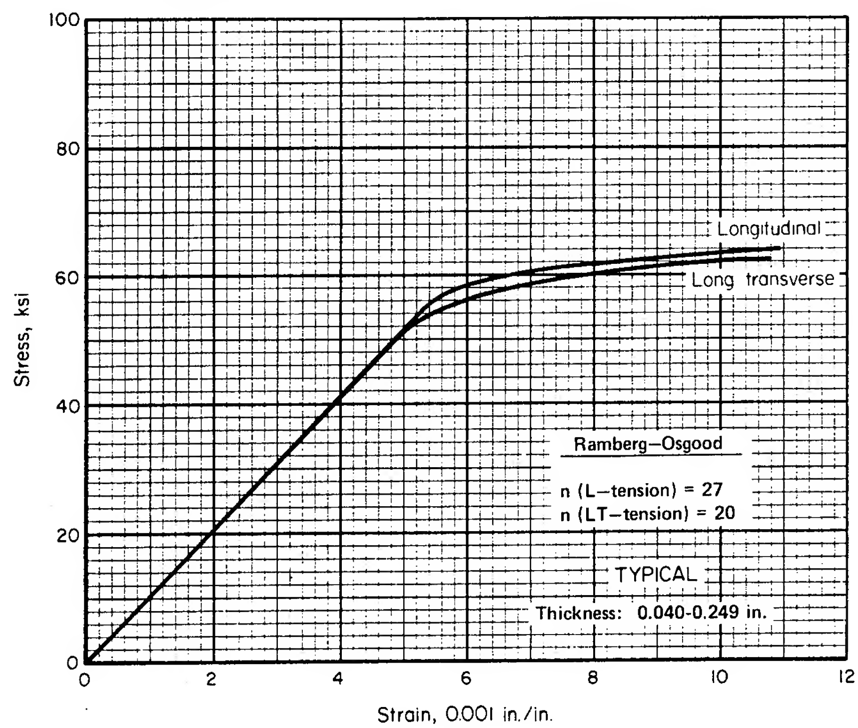

FIGURE 3.2.1.1.6(b). *Typical tensile stress-strain curves for clad 2014-T6 aluminum alloy sheet at room temperature.*

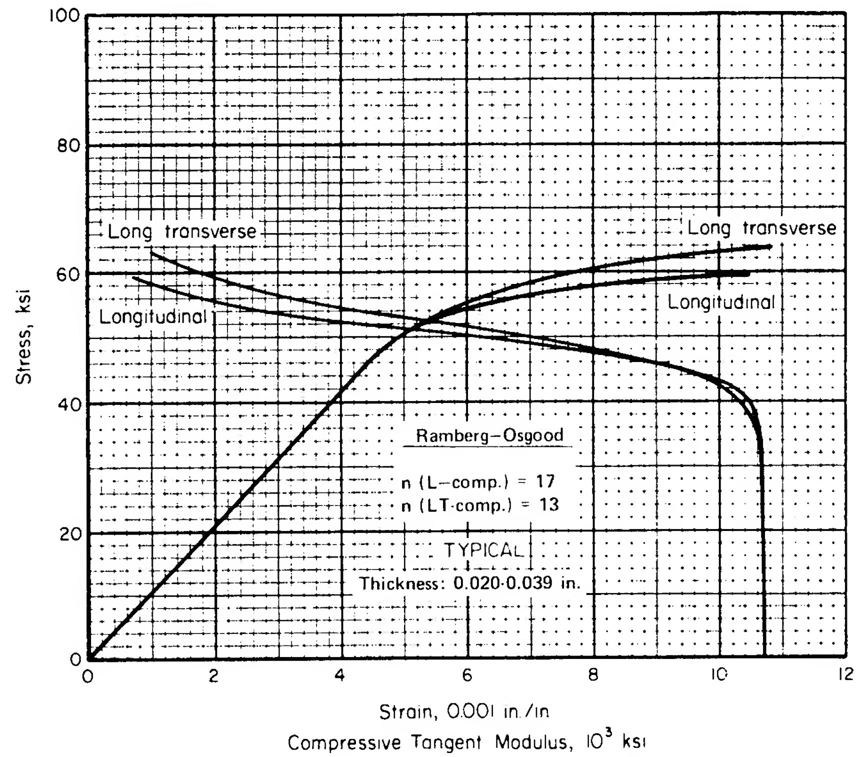

FIGURE 3.2.1.1.6(c). *Typical compressive stress-strain and compressive tangent-modulus curves for clad 2014-T6 aluminum alloy sheet at room temperature.*

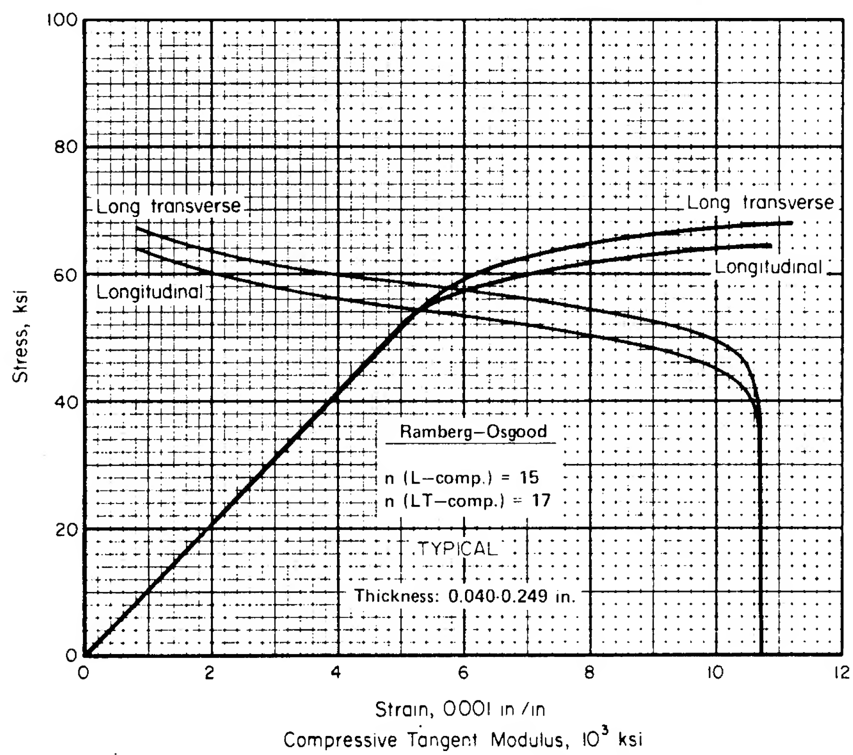

FIGURE 3.2.1.1.6(d). *Typical compressive stress-strain and compressive tangent-modulus curves for clad 2014-T6 aluminum alloy sheet at room temperature.*

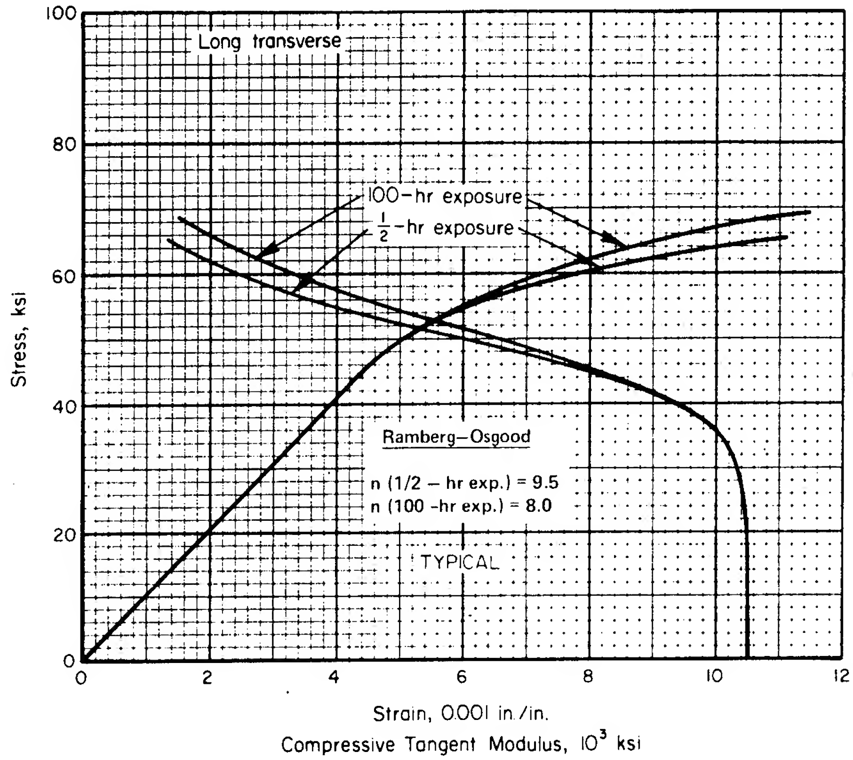

FIGURE 3.2.1.1.6(e). *Typical compressive stress-strain and compressive tangent-modulus curves for clad 2014-T6 aluminum alloy sheet at 200 F.*

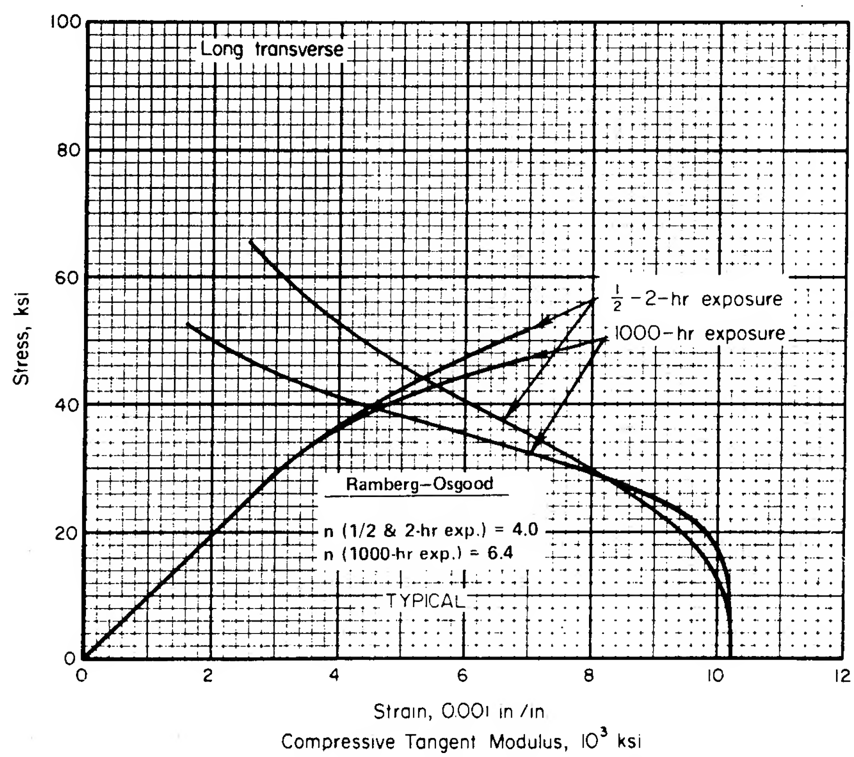

FIGURE 3.2.1.1.6(f). *Typical compressive stress-strain and compressive tangent-modulus curves for clad 2014-T6 aluminum alloy sheet at 300 F.*

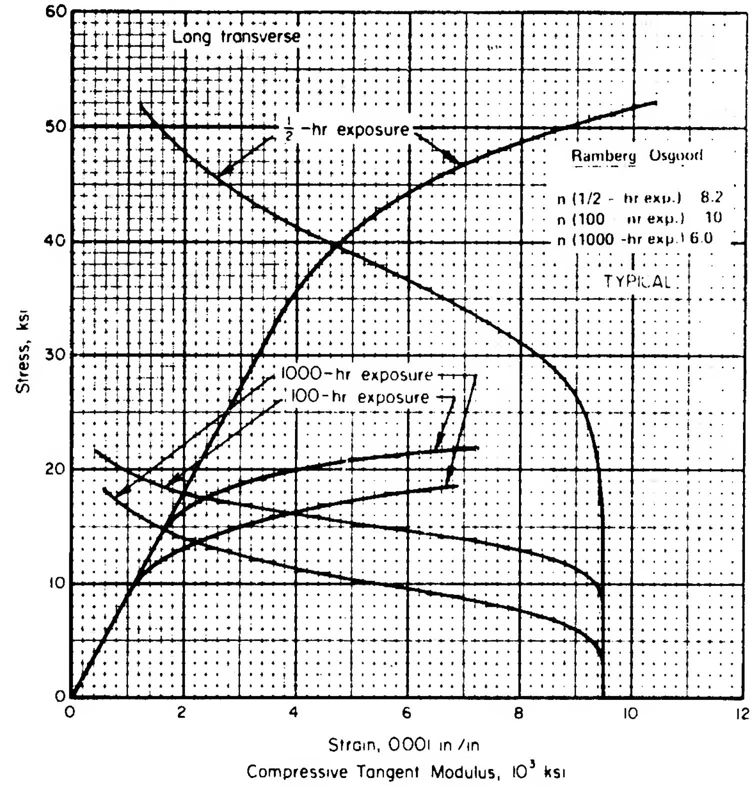

FIGURE 3.2.1.1.6(g). *Typical compressive stress-strain and compressive tangent-modulus curves for clad 2014-T6 aluminum alloy sheet at 400 F.*

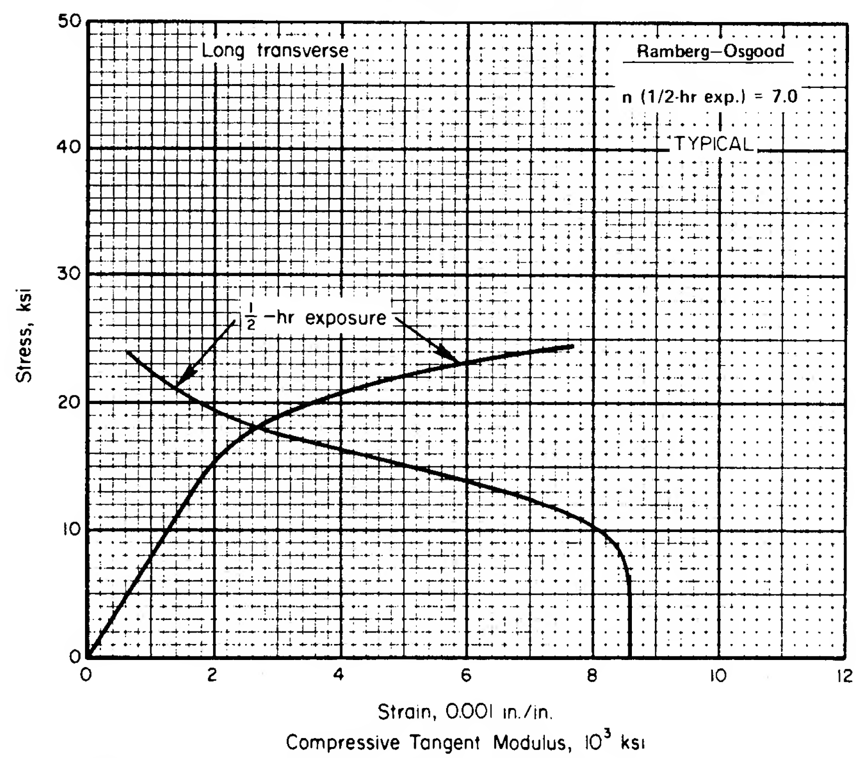

FIGURE 3.2.1.1.6(h). *Typical compressive stress-strain and compressive tangent-modulus curves for clad 2014-T6 aluminum alloy sheet at 500 F.*

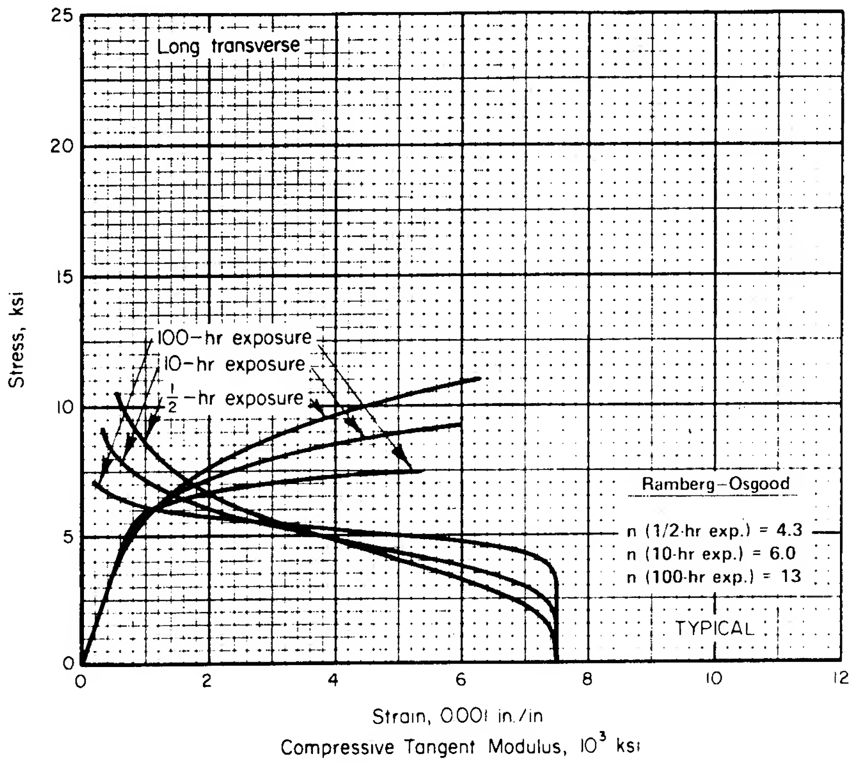

FIGURE 3.2.1.1.6(i). *Typical compressive stress-strain and compressive tangent-modulus curves for clad 2014-T6 aluminum alloy sheet at 600 F.*

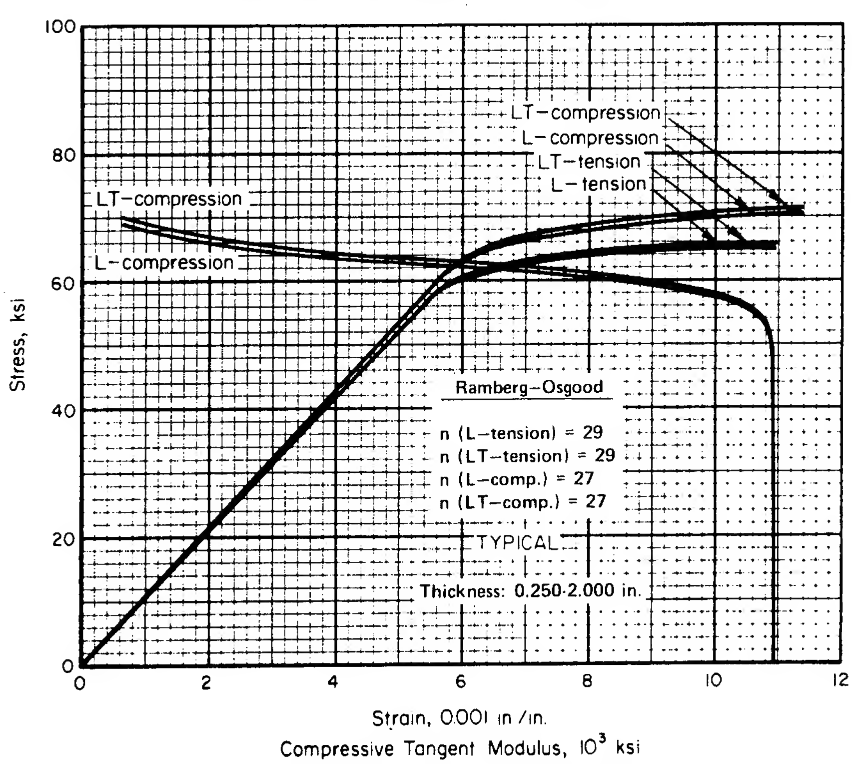

FIGURE 3.2.1.1.6(j). *Typical compressive stress-strain and compressive tangent-modulus curves for clad 2014-T62 aluminum alloy plate at room temperature.*

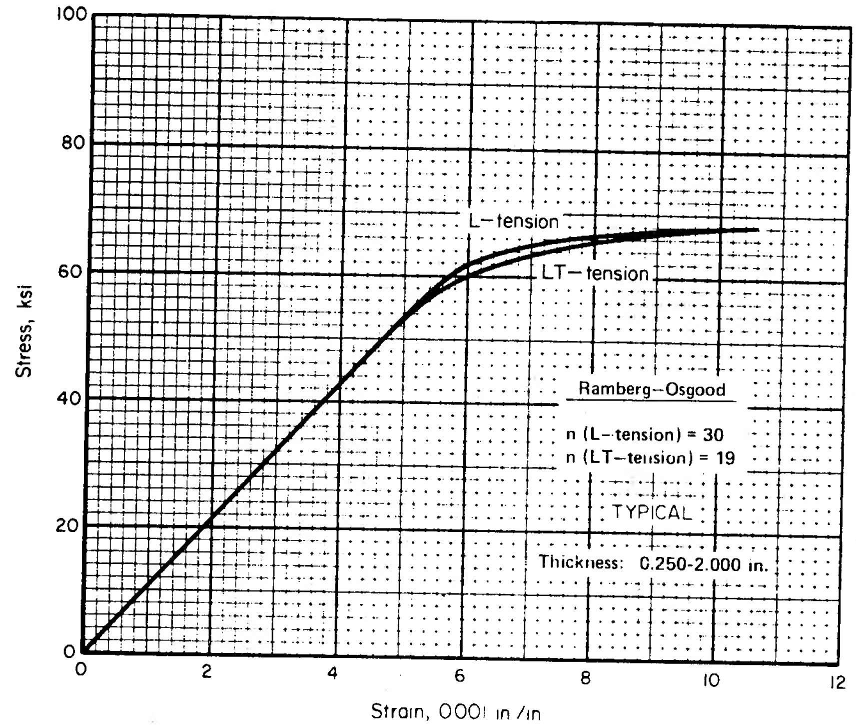

FIGURE 3.2.1.1.6(k). *Typical tensile stress-strain curves for 2014-T651 aluminum alloy plate at room temperature.*

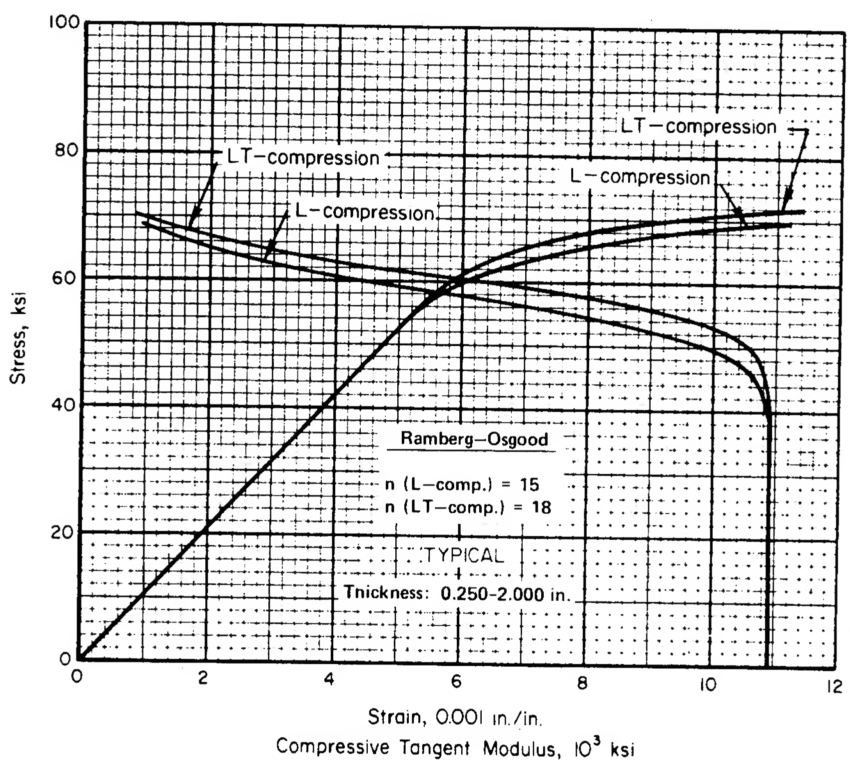

FIGURE 3.2.1.1.6(l). *Typical compressive stress-strain and compressive tangent-modulus curves for 2014-T651 aluminum alloy plate at room temperature.*

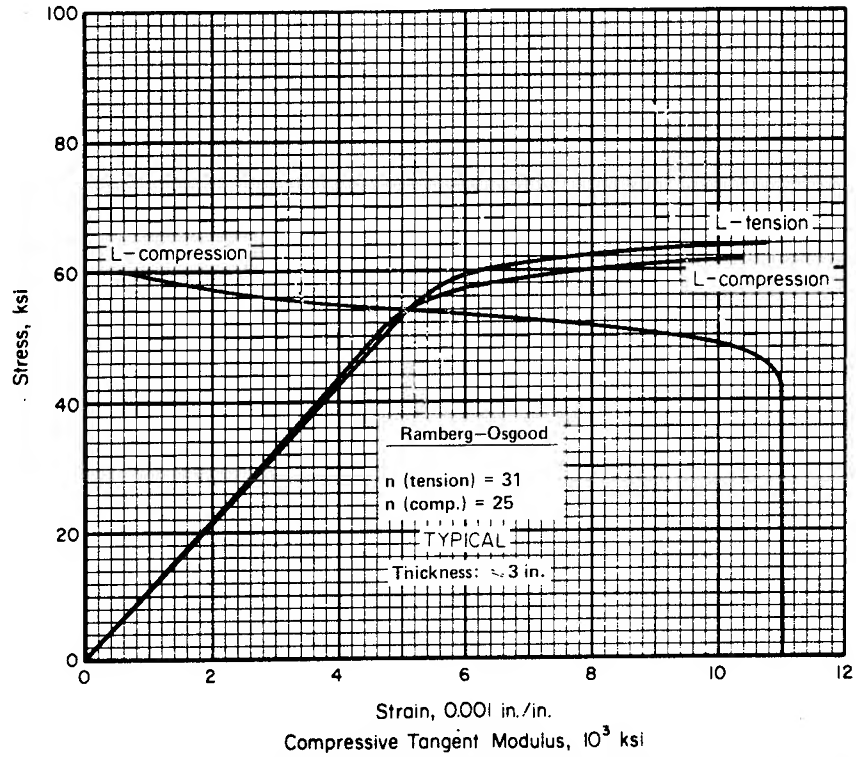

FIGURE 3.2.1.1.6(m). *Typical tensile and compressive stress-strain and compressive tangent-modulus curves for 2014-T6 aluminum alloy rolled bar, rod, and shapes at room temperature.*

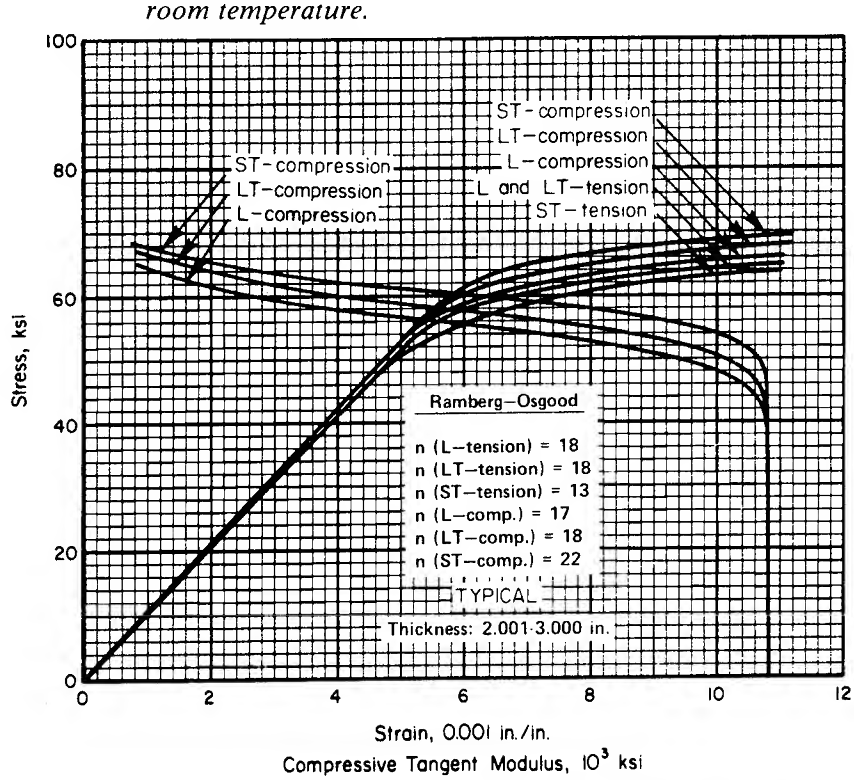

FIGURE 3.2.1.1.6(n). *Typical tensile and compressive stress-strain and compressive tangent-modulus curves for 2014-T652 aluminum alloy hand forging at room temperature.*

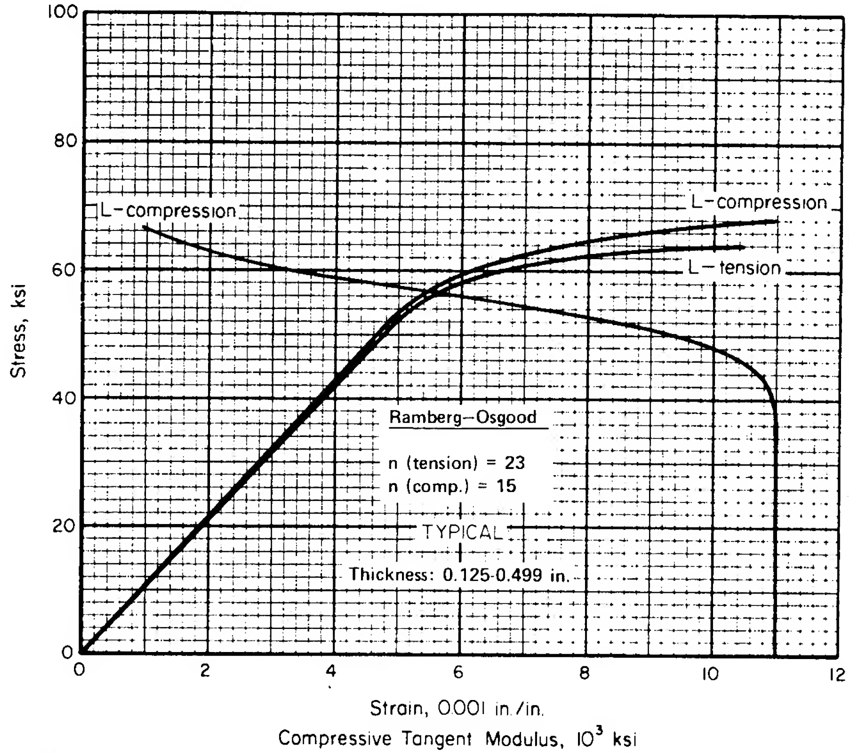

FIGURE 3.2.1.1.6(o). *Typical tensile and compressive stress-strain and compressive tangent-modulus curves for 2014-T6 aluminum alloy extrusion at room temperature.*

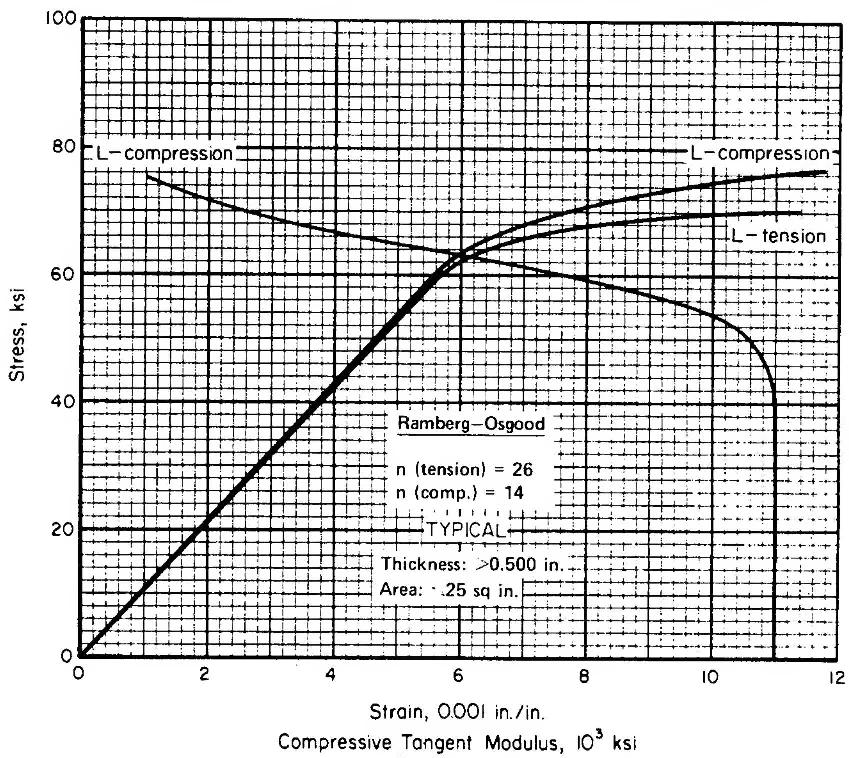

FIGURE 3.2.1.1.6(p). *Typical tensile and compressive stress-strain and compressive tangent-modulus curves for 2014-T6 aluminum alloy extrusion at room temperature.*

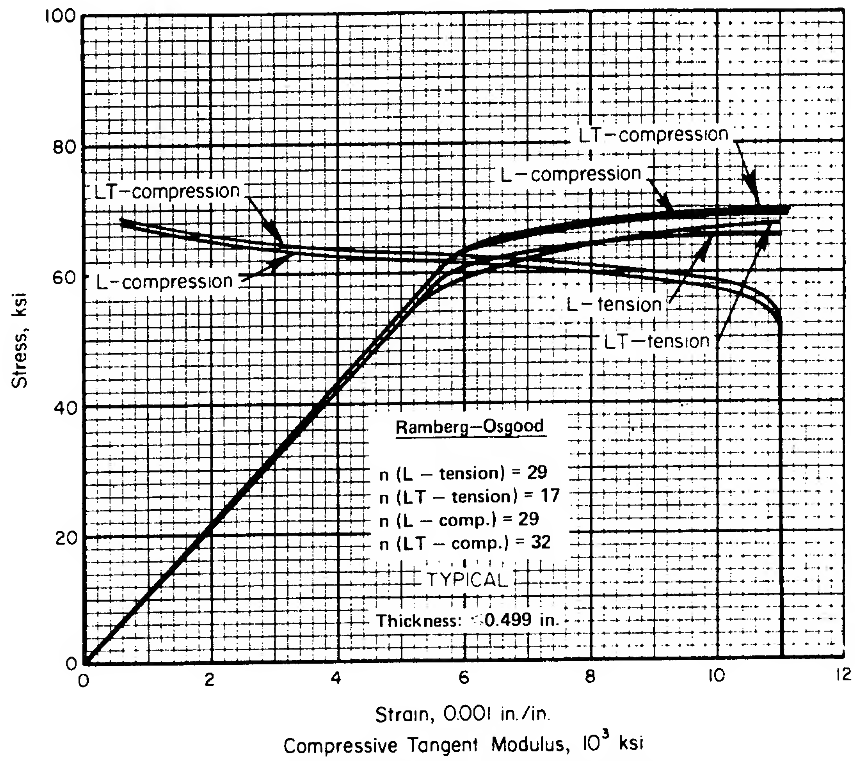

FIGURE 3.2.1.1.6(q). *Typical tensile and compressive stress-strain and compressive tangent-modulus curves for 2014-T62 aluminum alloy extrusion at room temperature.*

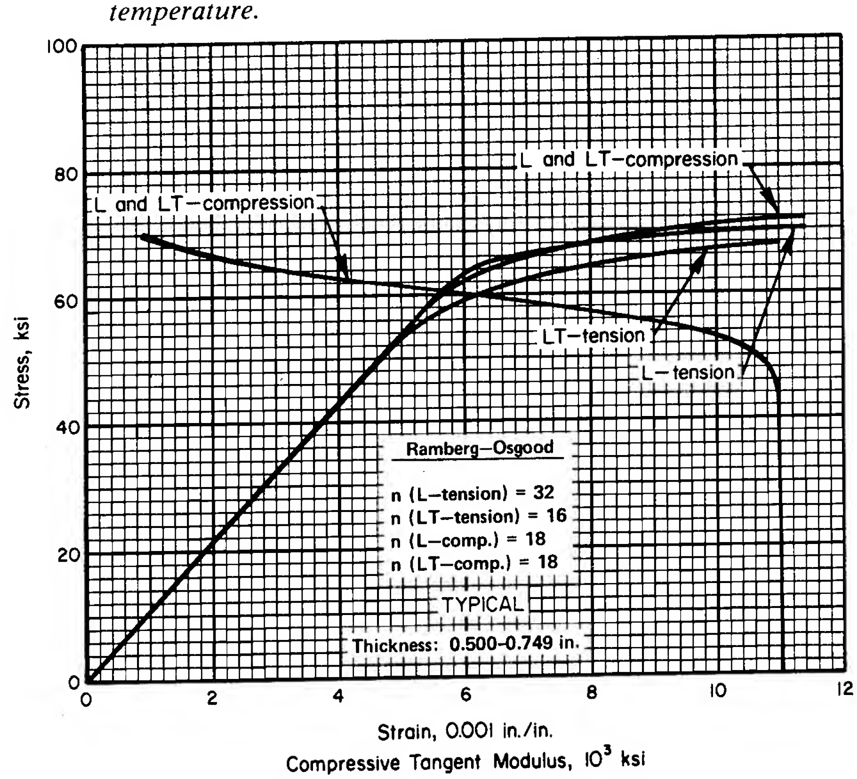

FIGURE 3.2.1.1.6(r). *Typical tensile and compressive stress-strain and compressive tangent-modulus curves for 2014-T651X aluminum alloy extrusion at room temperature.*

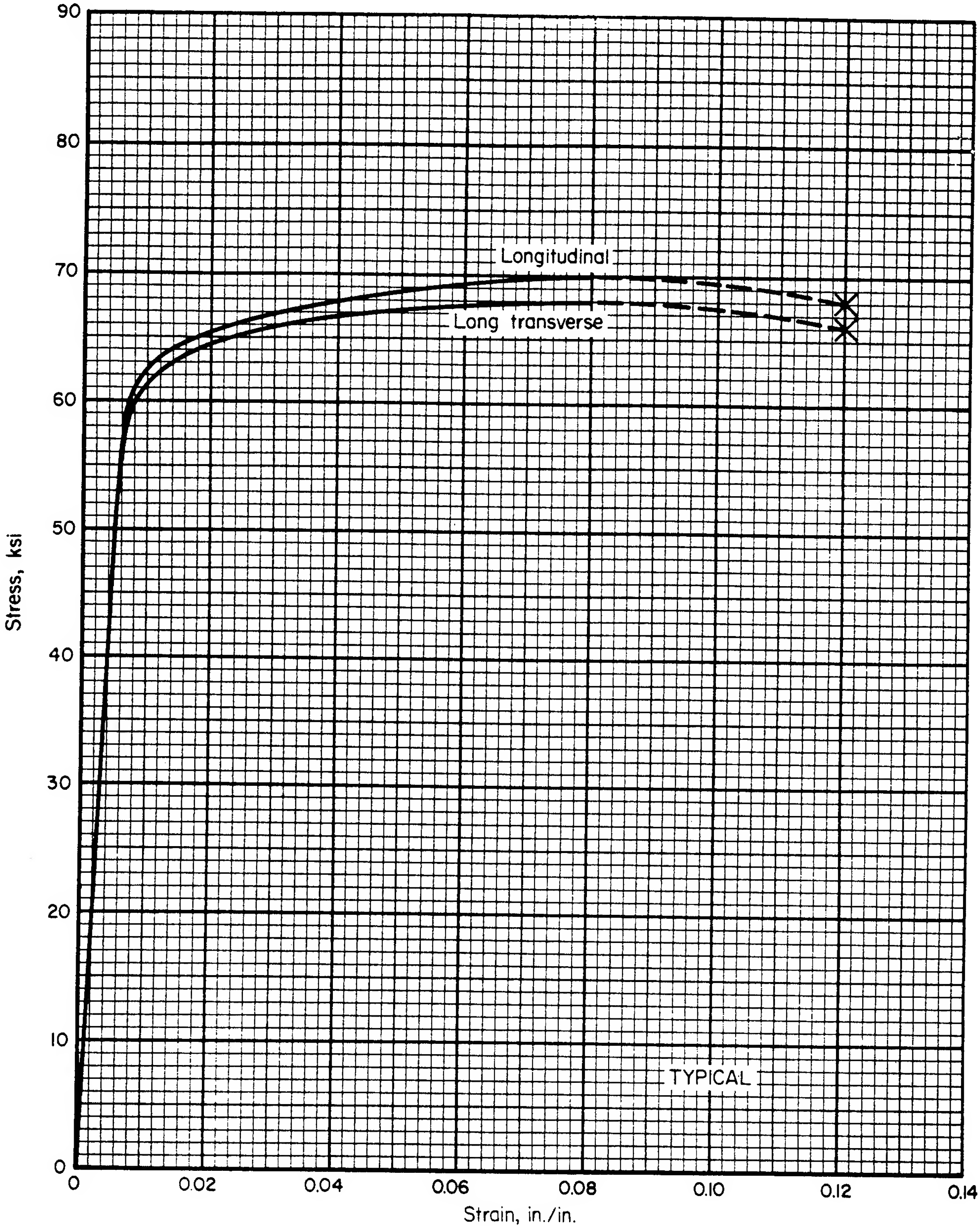

FIGURE 3.2.1.1.6(s). *Typical tensile stress-strain curves (full range) for 2014-T6 aluminum alloy forging at room temperature.*

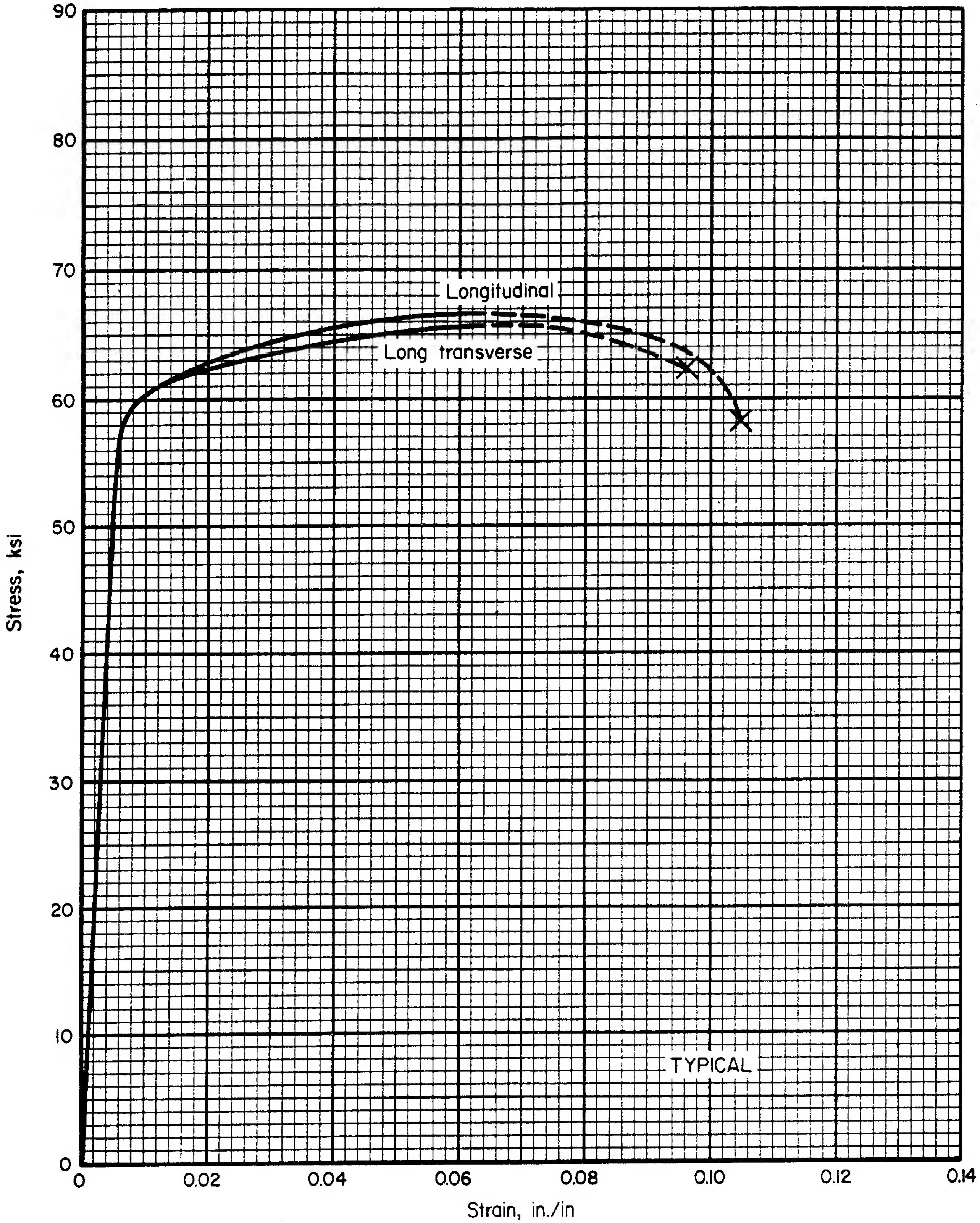

FIGURE 3.2.1.1.6(t). *Typical tensile stress-strain curves (full range) for 2014-T652 aluminum alloy forging at room temperature.*

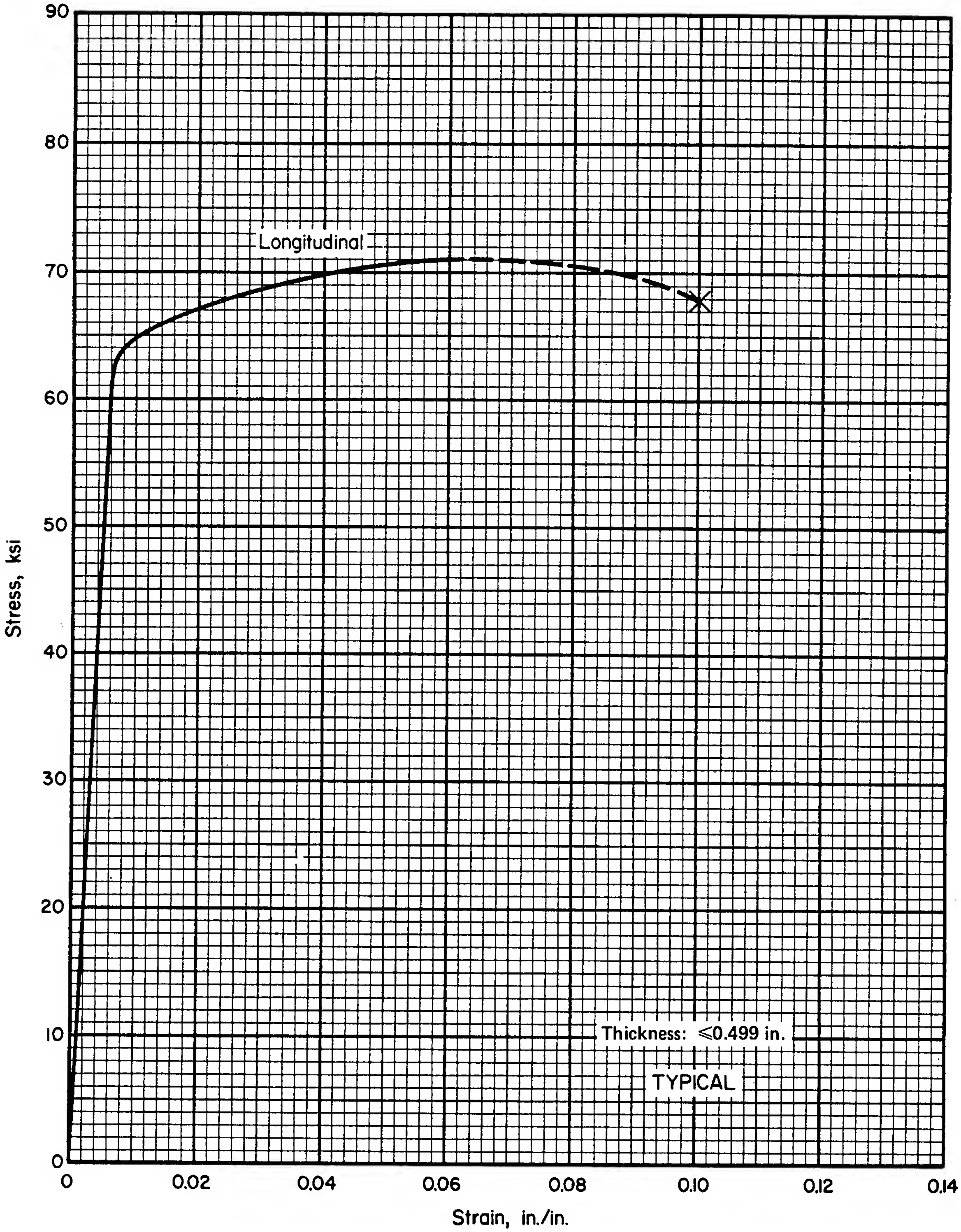

FIGURE 3.2.1.1.6(u). *Typical tensile stress-strain curve (full range) for 2014-T62 aluminum alloy extrusion at room temperature.*

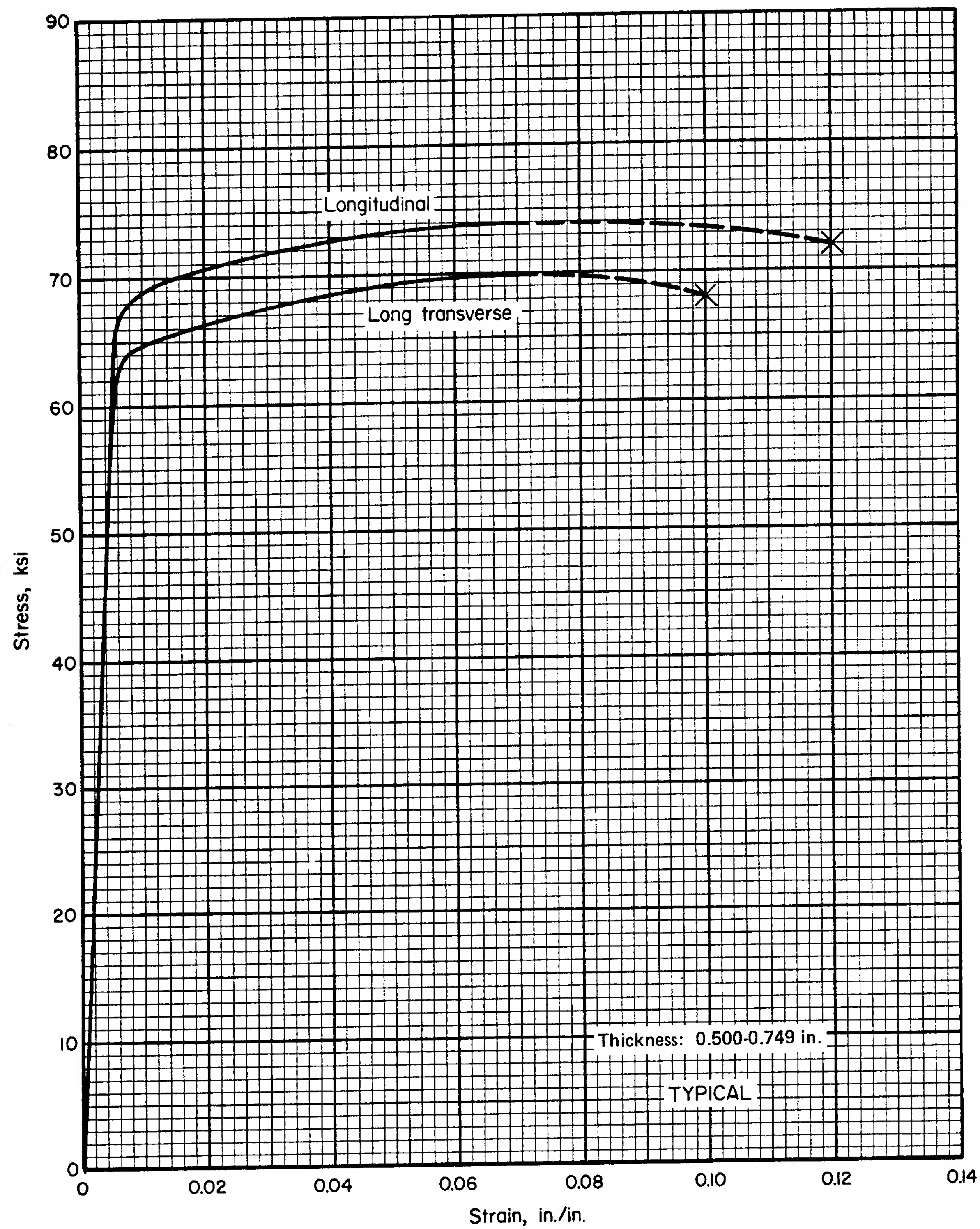

FIGURE 3.2.1.1.6(v). *Typical tensile stress-strain curves (full range) for 2014-T651X aluminum alloy extrusion at room temperature.*

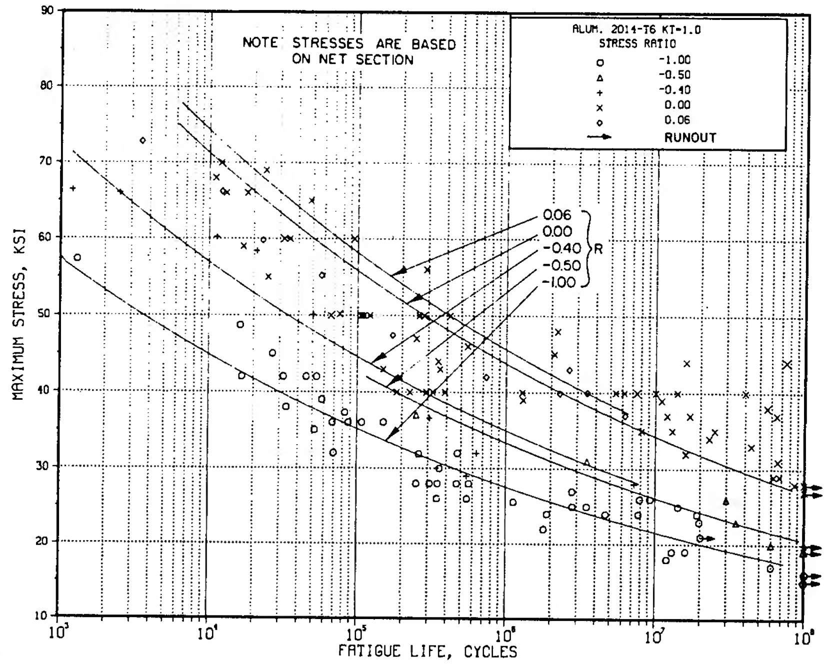

FIGURE 3.2.1.1.8(a). *Best-fit S/N curves for unnotched 2014-T6 aluminum alloy, various wrought products, longitudinal direction.*

Correlative Information for Figure 3.2.1.1.8(a)

Product Form: Drawn rod, 3/4-inch diameter
Rolled bar, 1 x 7-1/2-inch and 1-1/8-inch diameter
Rolled rod, 4-1/2-inch diameter
Extruded rod, 1-1/4-inch diameter
Extruded bar, 1-1/4 x 4 inch
Hand forging, 3 x 6 inch
Die forging, 4-1/2-inch diameter
Forged slab, 7/8 inch

Properties:	TUS, ksi	TYS, ksi	Temp., F
	67–78	60–72	RT

Specimen Details: Unnotched

Gross diameter, inches	Net Diameter, inches
1.00	0.400
0.273	0.100
—	0.200
—	0.160
1.00	0.500

Surface Condition:
Mechanically polished and as-machined

References: 3.2.1.1.8(a), (b), (d), and (e)

Test Parameters:

Loading - Axial
Frequency - 1100 to 3600 cpm
Temperature - RT
Environment - Air

No. of Heats/Lots: Not specified

Equivalent Stress Equation:

Log N_f = 21.49–9.44 log (S_{eq})
$S_{eq} = S_{max} (1-R)^{0.67}$
Standard Error of Estimate = 0.51
Standard Deviation in Life = 1.25
R^2 = 83%

Sample Size = 127

[Caution: The equivalent stress model may provide unrealistic life predictions for stress ratios beyond those represented above]

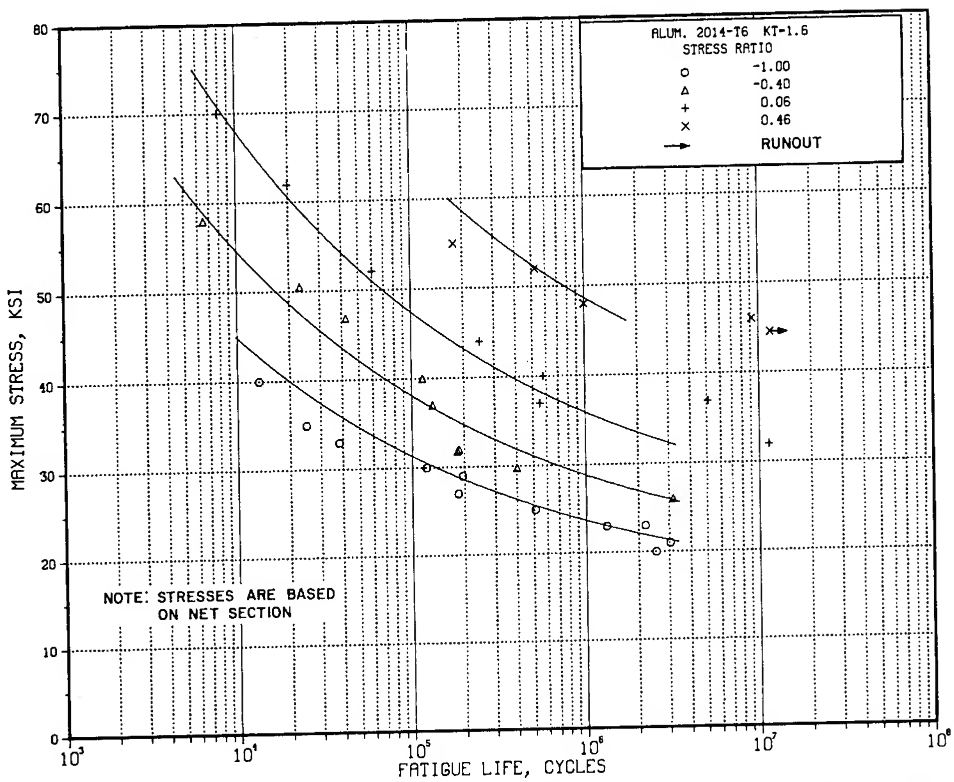

FIGURE 3.2.1.1.8(b). *Best-fit S/N curves for notched, K_t = 1.6, 2014-T6 aluminum alloy rolled bar, longitudinal direction.*

Correlative Information for Figure 3.2.1.1.8(b)

Product Form: Rolled bar, 1-1/8-inch diameter

Properties:

TUS, ksi	TYS, ksi	Temp., F
72	64	RT

Specimen Details: Semicircular circumferential notch, K_t = 1.6
0.45-inch gross diameter
0.4-inch net diameter
0.01-inch root radius
60° flank angle, ω

Surface Condition: Polished

Reference: 3.2.1.1.8(b)

Test Parameters:

Loading - Axial
Frequency - 3600 cpm
Temperature - RT
Environment - Air

No. of Heats/Lots: Not specified

Equivalent Stress Equation:

$\text{Log } N_f = 10.65 - 4.02 \log (S_{eq} - 20.2)$
$S_{eq} = S_{max} (1-R)^{0.55}$
Standard Error of Estimate = 0.33
Standard Deviation in Life = 0.87
R^2 = 86%

Sample Size = 33

[Caution: The equivalent stress model may provide unrealistic life predictions for stress ratios beyond those represented above]

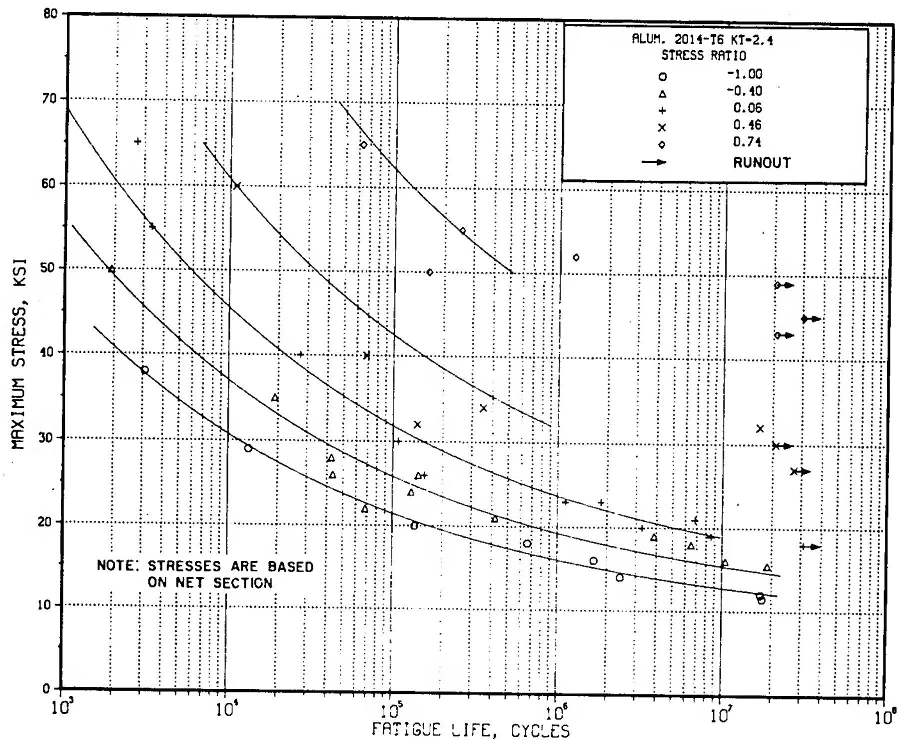

FIGURE 3.2.1.1.8(c). *Best-fit S/N curves for notched, K_t = 2.4, 2014-T6 aluminum alloy rolled bar, longitudinal direction.*

Correlative Information for Figure 3.2.1.1.8(c)

Product Form: Rolled bar, 1-1/8-inch diameter

Properties:

TUS, ksi	TYS, ksi	Temp., F
72	64	RT

Specimen Details: Circumferential V-Notch, K_t = 2.4

0.500-inch gross diameter
0.400-inch net diameter
0.032-inch notch radius
60° flank angle, ω

Surface Condition: Polished

Reference: 3.2.1.1.8(b)

Test Parameters:

Loading - Axial
Frequency - 1800 cpm
Temperature - RT
Environment - Air

No. of Heats/Lots: Not specified

Equivalent Stress Equation:

Log N_f = 10.59–4.36 log (S_{eq} – 11.7)
$S_{eq} = S_{max} (1-R)^{0.52}$
Standard Error of Estimate = 0.38
Standard Deviation in Life = 1.18
R^2 = 75%

Sample Size = 39

[Caution: The equivalent stress model may provide unrealistic life predictions for stress ratios beyond those represented above]

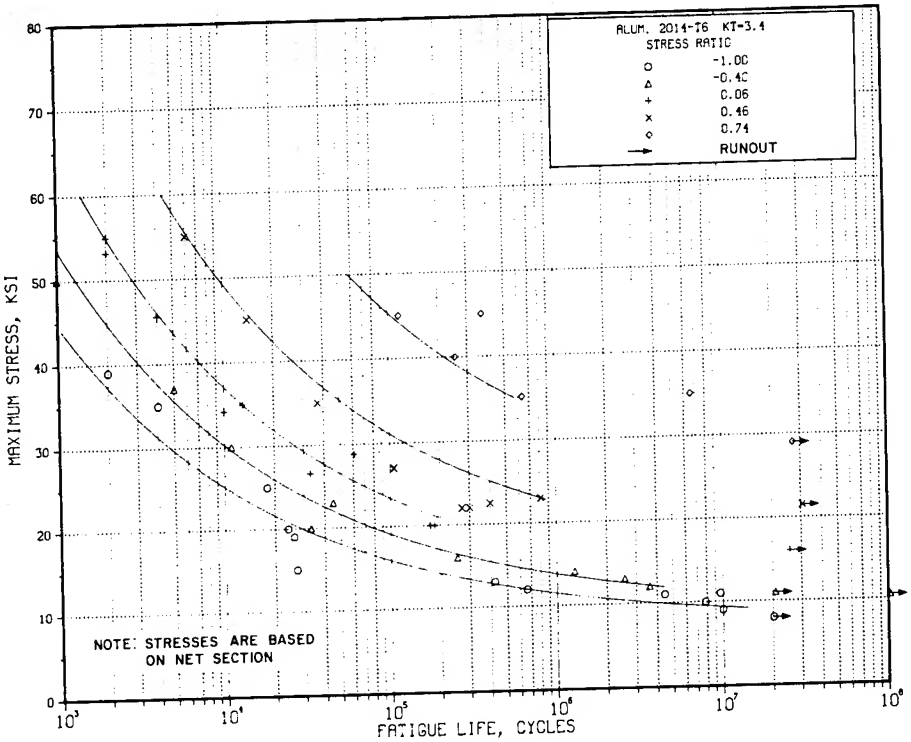

FIGURE 3.2.1.1.8(d). *Best-fit S/N curves for notched, K_t = 3.4, 2014-T6 aluminum alloy rolled and extruded bar, longitudinal direction.*

Correlative Information for Figure 3.2.1.1.8(d)

Product Form: Extruded bar, 1-1/8-inch diameter

Properties:

TUS, ksi	TYS, ksi	Temp., F
75	67	RT

Specimen Details: Circumferential V-notch, K_t = 3.4

0.450-inch gross diameter
0.400-inch net diameter
0.010-inch notch radius
60° flank angle, ω

Surface Condition: Smooth machine finish

References: 3.2.1.1.8(b) and (c)

Test Parameters:

Loading - Axial
Frequency - 3600 cpm
Temperature - RT
Environment - Air

No. of Heats/Lots: Not specified

Equivalent Stress Equation:

Log N_f = 8.35–3.10 log (S_{eq} - 10.6)
$S_{eq} = S_{max} (1-R)^{0.52}$
Standard Error of Estimate = 0.34
Standard Deviation in Life = 1.10
R^2 = 90%

Sample Size = 45

[Caution: The equivalent stress model may provide unrealistic life predictions for stress ratios beyond those represented above]

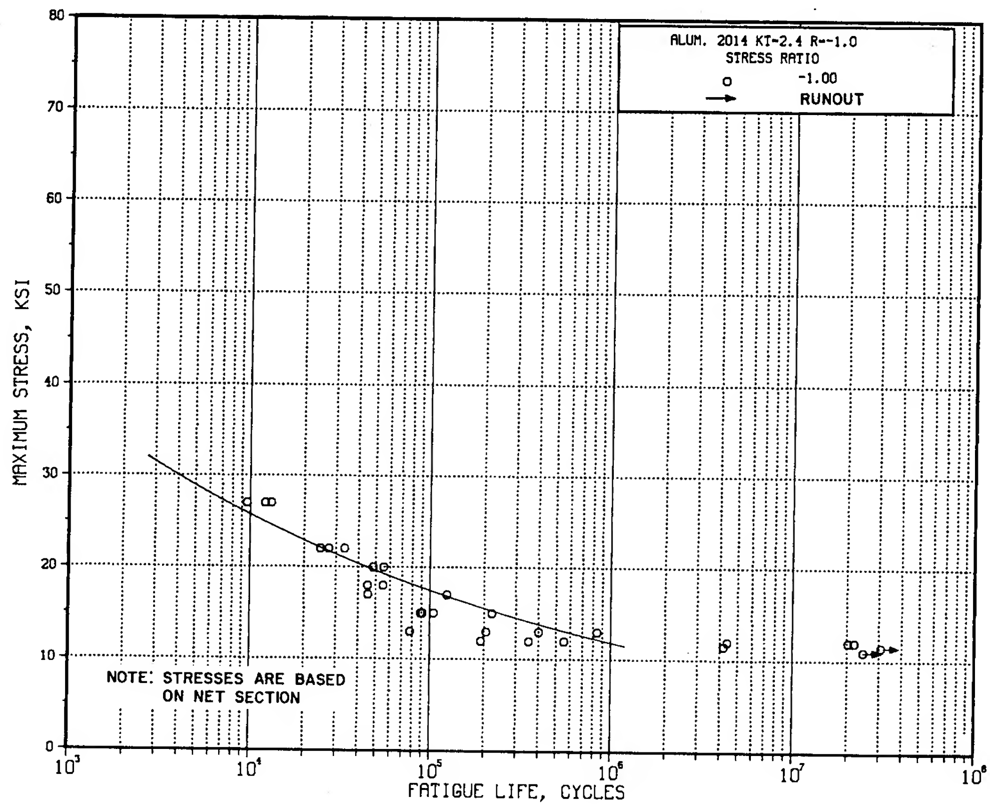

FIGURE 3.2.1.1.8(e). *Best-fit S/N curve for notched, K_t = 2.4, 2014-T6 aluminum alloy hand forging, longitudinal and short transverse directions.*

Correlative Information for Figure 3.2.1.1.8(e)

Product Form: Hand forging, 3 x 6 inch

Properties:	TUS, ksi	TYS, ksi	Temp., F
	Not Specified		RT

Specimen Details: Circumferential V-notch, K_t = 2.4

0.273-inch gross diameter
0.100-inch net diameter
0.010-inch notch radius
60° flank angle, ω

Surface Condition: Mechanically polished

References: 3.2.1.1.8(d)

Test Parameters:

Loading – Axial
Frequency – Not specified
Temperature – RT
Environment – Air

No. of Heats/Lots: Not specified

Equivalent Stress Equation:

Log N_f = 12.4–5.95 log (S_{max})
Standard Error of Estimate = 0.53
Standard Deviation in Life = 0.91
R^2 = 66%

Sample Size = 28

[Caution: The equivalent stress model may provide unrealistic life predictions for stress ratios beyond those represented above]

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3.2.2 2017 ALLOY

3.2.2.0 *Comments and Properties.*—2017 is a heat-treatable Al-Cu alloy available in the form of rolled bar, rod, and wire, and is used principally for fasteners. Refer to Section 3.1.3.4 for comments regarding the weldability of the alloy.

A material specification for 2017 aluminum alloy is presented in Table 3.2.2.0(a). Room-temperature mechanical and physical properties are shown in Table 3.2.2.0(b). Figure 3.2.2.0 shows the effect of temperature on thermal expansion.

TABLE 3.2.2.0(a). *Material Specification for 2017 Aluminum Alloy*

Specification	Form
QQ-A-225/5	Rolled bar and rod
AMS 4118	Bar and rod, rolled or cold-finished

The temper index for 2017 is as follows:

Section	Temper
3.2.2.1	T4, T451, and T42

3.2.2.1 *T4, T451, and T42 Temper.*—The effect of temperature on modulus elasticity is presented in Figure 3.2.2.1.4.

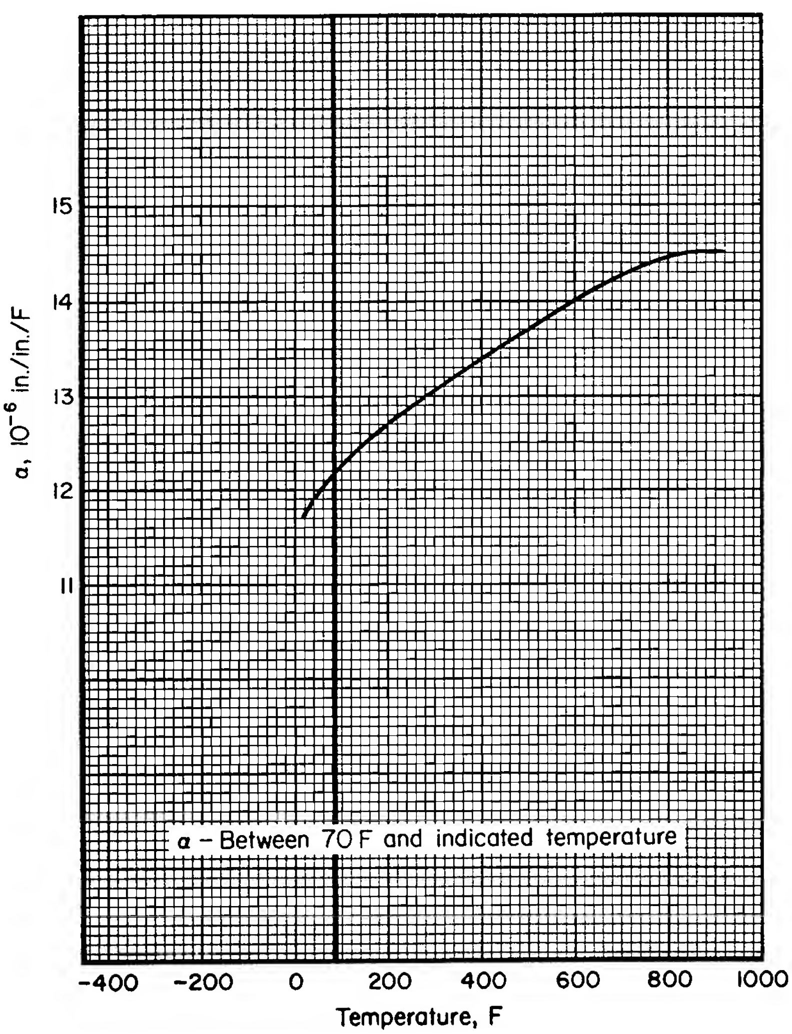

FIGURE 3.2.2.0. *Effect of temperature on the thermal expansion of 2017 aluminum alloy.*

TABLE 3.2.2.0(b). *Design Mechanical and Physical Properties of 2017 Aluminum Alloy Bar and Rod; Rolled, Drawn, or Cold-Finished*

Specification	AMS 4118 and QQ-A-225/5
Form	Bar and rod; rolled, drawn, or cold-finished
Temper	T4, T451, T42[a]
Cross-sectional area, in.^{2}	≤50
Thickness or diameter, in.	≤8.000
Basis	S
Mechanical Properties:	
F_{tu}, ksi:	
L	55
LT	...
F_{ty}, ksi:	
L	32
LT	...
F_{cy}, ksi:	
L	32[b]
LT	...
F_{su}, ksi	33
F_{bru}, ksi:	
(e/D = 1.5)	83
(e/D = 2.0)	105
F_{bry}, ksi:	
(e/D = 1.5)	45
(e/D = 2.0)	51
e, percent (S-basis):	
L	12
E, 10^3 ksi	10.4
E_c, 10^3 ksi	10.6
G, 10^3 ksi	3.95
μ	0.33
Physical Properties:	
ω, lb/in.^{3}	0.101
C, Btu/(lb)(F)	0.23 (at 212 F)
K, Btu/[(hr)(ft^2)(F)/ft]	78 (at 77 F)
α, 10^{-6} in./in./F	See Figure 3.2.2.0

[a]Design allowables were based upon data obtained from testing T4 material and from testing samples of bar and rod, supplied in the O or F temper, which were heat treated to T42 temper to demonstrate response to heat treatment by suppliers.
[b]For the stress-relieved temper T451, the F_{cy} value may be somewhat lower.

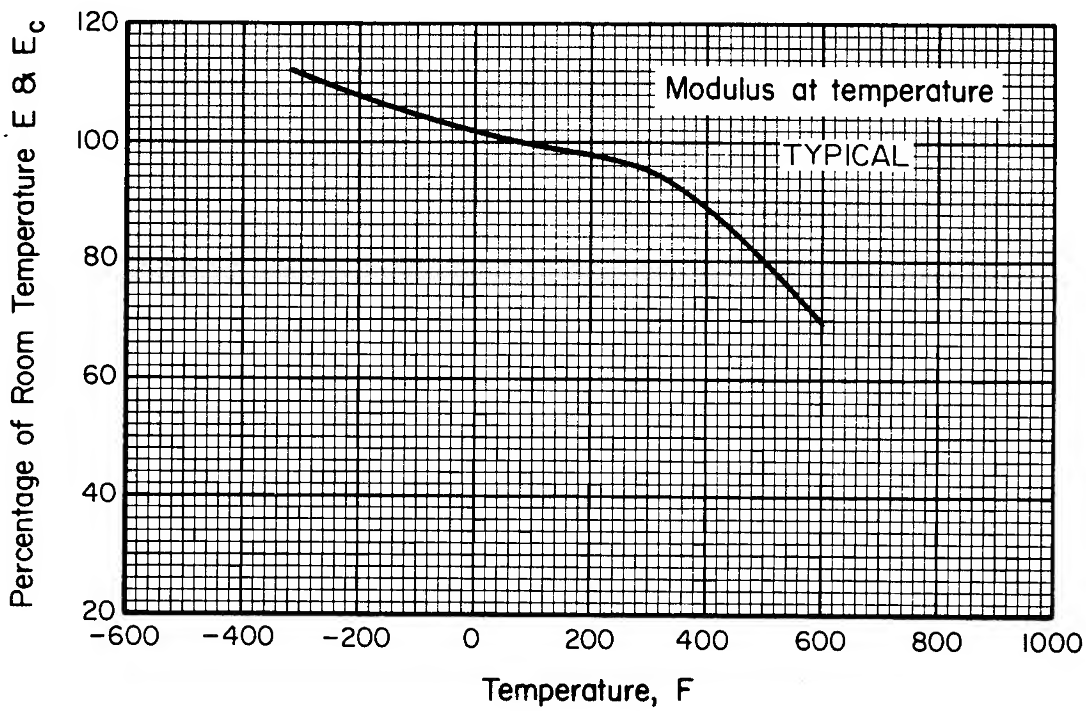

FIGURE 3.2.2.1.4. *Effect of temperature on the tensile and compression moduli (E and E_c) of 2017 aluminum alloy.*

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3.2.3 2024 ALLOY

3.2.3.0 *Comments and Properties.*—2024 is a heat-treatable Al-Cu alloy which is available in a wide variety of product forms and tempers. The properties vary markedly with temper; those in T3 and T4 type tempers are noteworthy for their high toughness, while T6 and T8 type tempers have very high strength. This alloy has excellent properties and creep resistance at elevated temperatures. The T6 and T8 type tempers have very high resistance to corrosion, while T3 and T4 type tempers should be considered in light of Section 3.1.2.3. Refer to Section 3.1.3.4 for comments regarding the weldability of the alloy.

Material specifications for 2024 are presented in Table 3.2.3.0(a). Room-temperature mechanical properties are shown in Tables 3.2.3.0(b) through (j_2). The effect of temperature on the physical properties of this alloy is shown in Figure 3.2.3.0.

TABLE 3.2.3.0(a). *Material Specifications for 2024 Aluminum Alloy*

Specification	Form
AMS 4037	Bare sheet and plate
AMS 4035	Bare sheet and plate
QQ-A-250/4	Bare sheet and plate
QQ-A-250/5	Clad sheet and plate
AMS 4120	Bar and rod, rolled or cold-finished
QQ-A-225/6	Rolled or drawn bar, rod, and wire
AMS 4086	Tubing, hydraulic, seamless, drawn
WW-T-700/3	Tubing
AMS 4152	Extrusion
AMS 4164	Extrusion
AMS 4165	Extrusion
QQ-A-200/3	Extruded bar, rod, and shapes

The following temper designations are more specifically described than in Table 3.1.2.:

T81—The applicable designation for 2024-T3 sheet artificially aged to the required strength level.

T361—Solution heat treated and naturally aged followed by cold rolling and natural aging treatment.

T861—Solution heat treated and naturally aged followed by cold rolling and artificial aging treatment.

T72—Solution heat treated and aged by user in accordance with MIL-H-6088 to provide high resistance to stress-corrosion cracking, applicable only to sheet.

The temper index for 2024 is as follows:

Section	Temper
3.2.3.1	T3, T351, T3510, T3511, T4, and T42
3.2.3.2	T361 (supersedes T36)
3.2.3.3	T62 and T72
3.2.3.4	T81, T851, T8510, and T8511
3.2.3.5	T861 (supersedes T86)

3.2.3.1 *T3, T351, T3510, T3511, T4, and T42 Temper.*—Figures 3.2.3.1.1(a) through 3.2.3.1.5(b) present elevated temperature curves for various properties. Figures 3.2.3.1.6(a) through (q) present tensile and compressive stress-strain curves and tangent-modulus curves for various product forms and tempers at various temperatures. Figures 3.2.3.1.6(r) through (w) are full-range, stress-strain curves at room temperature for various product forms. Figures 3.2.3.1.8(a) through (i) provide S/N fatigue curves for unnotched and notched specimens for T3 and T4 tempers.

3.2.3.2 *T361 (supersedes T36) Temper.*

3.2.3.3 *T62 and T72 Temper.*—Figures 3.2.3.3.1(a) through (d) and 3.2.3.3.5(a) and (b) show the effect of temperature on the tensile properties of the T62 temper. Figure 3.2.3.1.4 can be used for the elevated temperature curve for elastic moduli for this temper. Tensile and compressive stress-strain and tangent-modulus curves at room temperature are shown in Figure 3.2.3.3.6.

3.2.3.4 *T81, T851, T852, T8510, and T8511 Temper.*—Figures 3.2.3.4.1(a) through (d), 3.2.3.4.2(a) and (b), 3.2.3.4.3(a) and (b), and 3.2.3.4.5(a) and (b) present elevated temperature curves for various mechanical properties for the T8XXX temper. Figures 3.2.3.4.1(e) and (f) contain graphs for determining tensile properties after complex thermal exposure. See Section 3.7.4.1 for a detailed discussion of their use. Figures 3.2.3.4.6(a) through (g) present tensile and compressive stress-strain and tangent-modulus curves for various products and tempers. Figures

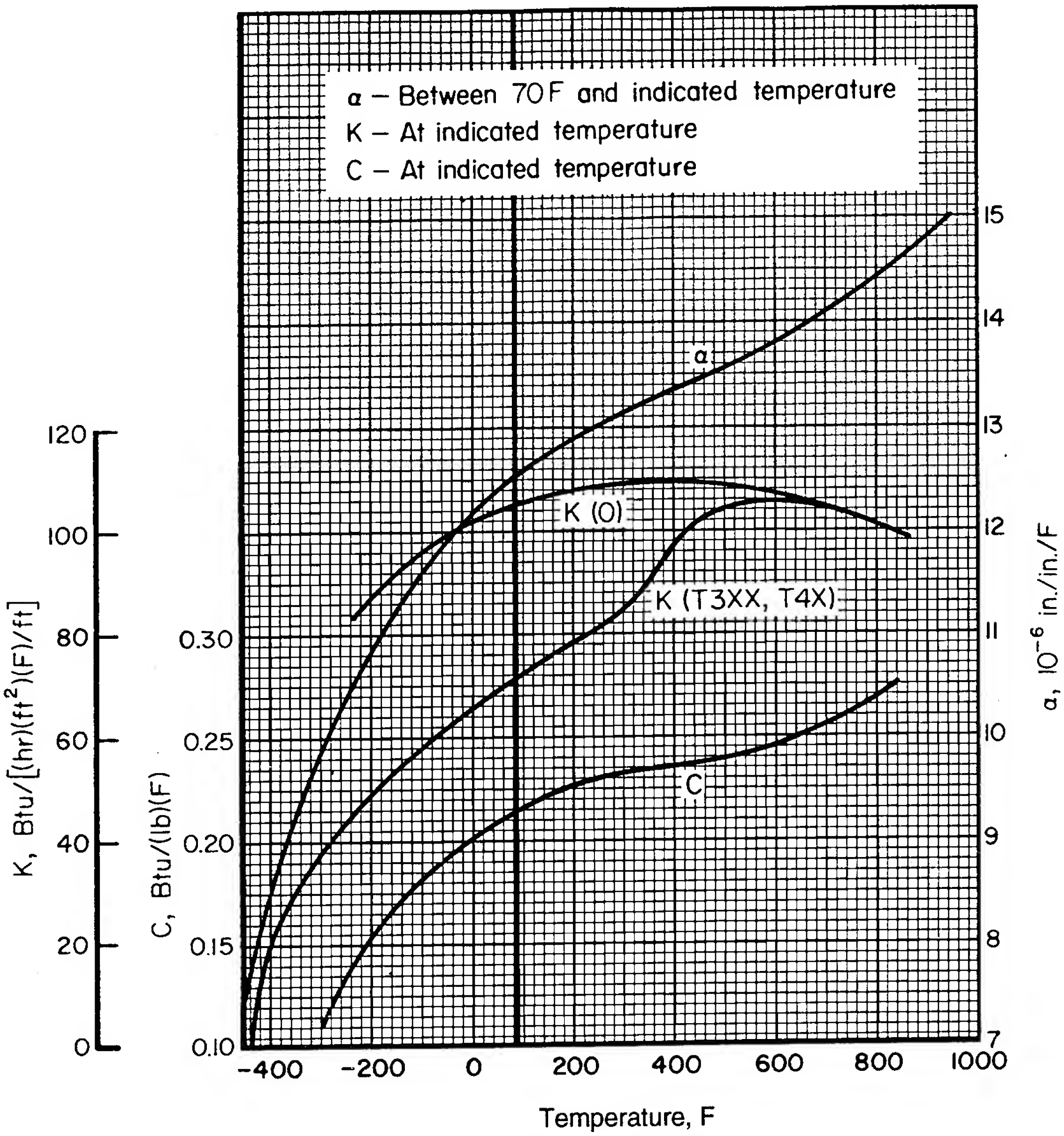

FIGURE 3.2.3.0. *Effect of temperature on the physical properties of 2024 aluminum alloy.*

3.2.3.4.6(h) through (j) are full-range stress-strain curves at room temperature for various product forms.

3.2.3.5 *T861 (T86) Temper.*—Figures 3.2.3.5.1(a) and (b), 3.2.3.5.3(a) through (c), and 3.2.3.5.5(a) and (b) present effect-of-temperature curves for various mechanical properties. Figures 3.2.3.5.6(a) through (d) present compressive stress-strain and tangent-modulus curves for sheet material at various temperatures. Graphical displays of the residual strength behavior of center-cracked tension panels are presented in Figures 3.2.3.5.10(a) and (b).

TABLE 3.2.3.0(b$_1$). *Design Mechanical and Physical Properties of 2024 Aluminum Alloy Sheet and Plate*

Specification	AMS 4037 and QQ-A-250/4																	QQ-A-250/4		
Form	Sheet					Plate												Sheet		Plate
Temper	T3					T351												T361		
Thickness, in.	0.008-0.009	0.010-0.128		0.129-0.249		0.250-0.499		0.500-1.000		1.001-1.500		1.501-2.000		2.001-3.000		3.001-4.000		0.020-0.062	0.063-0.249	0.250-0.500
Basis	S	A	B	A	B	A	B	A	B	A	B	A	B	A	B	A	B	S	S	S
Mechanical Properties:																				
F_{tu}, ksi:																				
L	64	64	65	65	66	64	66	63	65	62	64	62	64	60	62	57	59	68	69	67
LT	63	63	64	64	65	64	66	63	65	62	64	62	64	60	62	57	59	67	68	66
ST	...	...	...	...	...	...	...	...	...	...	...	...	...	52	54	49	51	...	...	...
F_{ty}, ksi:																				
L	47	47	48	47	48	48	50	48	50	47	50	47	49	46	48	43	46	56	56	54
LT	42	42	43	42	43	42	44	42	44	42	44	42	44	42	44	41	43	50	51	49
ST	...	...	...	...	...	...	...	...	...	...	...	...	...	38	40	38	39	...	...	...
F_{cy}, ksi:																				
L	39	39	40	39	40	39	41	39	41	39	40	38	40	37	39	35	37	47	48	46
LT	45	45	46	45	46	45	47	45	47	44	46	44	46	43	45	41	43	53	54	52
ST	...	...	...	...	...	...	...	...	...	...	...	...	...	46	48	44	47	...	...	...
F_{su}, ksi	39	39	40	40	41	38	39	37	38	37	38	37	38	35	37	34	35	42	42	41
F_{bru}[a], ksi:																				
(e/D = 1.5)	104	104	106	106	107	97	100	95	98	94	97	94	97	91	94	86	89	111	112	109
(e/D = 2.0)	129	129	131	131	133	119	122	117	120	115	119	115	119	111	115	106	109	137	139	135
F_{bry}[a], ksi:																				
(e/D = 1.5)	73	73	75	73	75	72	76	72	76	72	76	72	76	72	76	70	74	82	84	81
(e/D = 2.0)	88	88	90	88	90	86	90	86	90	86	90	86	90	86	90	84	88	97	99	96
e, percent (S-basis):																				
LT	10	[b]	...	[b]	...	12	...	8	...	7	...	6	...	4	...	4	...	8	9	9[c]
E, 10^3 ksi	10.5					10.7												10.5		10.7
E_c, 10^3 ksi	10.7					10.9												10.7		10.9
G, 10^3 ksi	4.0					4.0												4.0		4.0
μ	0.33					0.33												0.33		0.33
Physical Properties:																				
ω, lb/in.	0.101																			
C, K, and α	See Figure 3.2.3.0																			

[a]Bearing values are "dry pin" values per Section 1.4.7.1. See Table 3.1.2.1.1.
[b]See Table 3.2.3.0(c).
[c]10% for 0.500 inch.

TABLE 3.2.3.0(b$_2$). *Design Mechanical and Physical Properties of 2024 Aluminum Alloy Sheet and Plate—Continued*

Specification	QQ-A-250/4		AMS 4035 and QQ-A-250/4						QQ-A-250/4					
Form	Coiled Sheet		Flat Sheet and Plate											
Temper	T4		T42[a]						T62[a]					T72[a]
Thickness, in.	0.010-0.249		0.010-0.071	0.072-0.249	0.250-0.499	0.500-1.000	1.001-2.000	2.001-3.000	0.010-0.071	0.072-0.249	0.250-0.499	0.500-2.000	2.001-3.000	0.010-0.249
Basis	A	B	S	S[b]	S[b]	S[b]	S[b,c]	S	S	S[b]	S[b]	S[b,c]	S	S
Mechanical Properties:														
F_{tu}, ksi:														
L	62	64	...	62	62	61	60	...	64	64	64	63	...	...
LT	62	64	62	62	62	61	60	58	64	64	64	63	63	60
F_{ty}, ksi:														
L	40	42	...	39	39	39	39	...	50	50	50	50	...	...
LT	40	42	...	38	38	38	38	38	50	50	50	50	50	46
F_{cy}, ksi:														
L	40	42	...	42	41	40	35	...	...	52	52	52	...	...
LT	40	42	...	41	41	41	41	...	...	52	52	52	...	...
F_{su}, ksi	37	38	...	41	40	37	30	...	...	41	40	34	...	...
F_{bru}, ksi:														
(e/D = 1.5)	93	96	...	99	97	91	80	...	...	103	103	102	...	...
(e/D = 2.0)	118	122	...	124	121	112	96	...	...	134	132	119	...	...
F_{bry}, ksi:														
(e/D = 1.5)	56	59	...	67	67	67	67	...	...	81	81	81	...	...
(e/D = 2.0)	64	67	...	79	79	79	79	...	...	93	93	93	...	...
e, percent (S-basis):														
LT	d	...	d	d	12	8	d	4	5	5	5	5	5	5
E, 10^3 ksi	See Table 3.2.3.0(d)													
E_c, 10^3 ksi	See Table 3.2.3.0(d)													
G, 10^3 ksi	See Table 3.2.3.0(d)													
μ	See Table 3.2.3.0(d)													
Physical Properties:														
ω, lb/in.^{3}	0.101													
C, Btu(lb)(F)	See Figure 3.2.3.0													
K, Btu[(hr)(ft^2)(F)/ft]	71 (at 77 F) for T4X and 87 (at 77 F) for T6X, T7X, See Figure 3.2.3.0													
α, 10^{-6} in./in./F	See Figure 3.2.3.0													

[a]Design allowables in some cases were based upon data obtained from testing samples of material, supplied in the O or F temper, which were heat treated to demonstrate response to heat treatment by suppliers. Properties obtained by the user may be different than those listed if the material has been formed or otherwise cold or hot worked, particularly in the annealed temper, prior to solution heat treatment.
[b]Bearing values are "dry pin" values per Section 1.4.7.1.
[c]See Table 3.1.2.1.1.
[d]See Table 3.2.3.0(c).

TABLE 3.2.3.0(b_3). *Design Mechanical and Physical Properties of 2024 Aluminum Alloy Sheet and Plate—Continued*

Specification	QQ-A-250/4								
Form	Sheet		Plate				Sheet		Plate
Temper	T81		T851[a]				T861[a]		
Thickness, in.	0.010-0.249		0.250-0.499		0.500-1.000	1.001-1.499	0.020-0.062	0.063-0.249	0.250-0.500
Basis	A	B	A	B	S	S[b]	S	S	S
Mechanical Properties:									
F_{tu}, ksi:									
L	67	68	67	68	66	66	71	72	70
LT	67	68	67	68	66	66	70	71	70
F_{ty}, ksi:									
L	59	61	58	60	58	57	63	67	64
LT	58	60	58	60	58	57	62	66	64
F_{cy}, ksi:									
L	59	61	58	60	58	56	63	67	64
LT	58	60	59	61	58	57	65	69	67
F_{su}, ksi	40	41	38	39	37	37	40	40	40
F_{bru}, ksi:									
(e/D = 1.5)	100	102	102	103	100	100	108	110	108
(e/D = 2.0)	127	129	131	133	129	129	140	142	140
F_{bry}, ksi:									
(e/D = 1.5)	83	86	86	89	86	85	90	96	93
(e/D = 2.0)	94	97	101	105	101	99	105	112	109
e, percent (S-basis):									
LT	5	...	5	...	5	5	3	4	4
E, 10^3 ksi	See Table 3.2.3.0(d)								
E_c, 10^3 ksi	See Table 3.2.3.0(d)								
G, 10^3 ksi	See Table 3.2.3.0(d)								
μ	See Table 3.2.3.0(d)								
Physical Properties:									
ω, lb/in.^{3}	0.101								
C, Btu(lb)(F)	See Figure 3.2.3.0								
K, Btu[(hr)(ft^2)(F)/ft]	87 (at 77 F)								
α, 10^{-6} in./in./F	See Figure 3.2.3.0								

[a]Bearing values are "dry pin" values per Section 1.4.7.1.
[b]See Table 3.1.2.1.1.

TABLE 3.2.3.0(c). *Minimum Elongation Values for Bare 2024 Aluminum Alloy Sheet and Plate*

Condition	Elongation (LT), percent
	T3, T4, and T42
Thickness, in.:	
0.010-0.020	12
0.021-0.249	15
0.250-0.499	12
0.500-1.000	8
1.001-1.500	7
1.501-2.000	6

TABLE 3.2.3.0(d). *Modulus Values and Poisson's Ratio for Bare 2024 Aluminum Alloy Sheet and Plate, All Tempers*

Property	E	E_c	G	μ
Thickness, in.:				
0.010-0.249	10.5	10.7	4.0	0.33
≥0.250	10.7	10.9	4.0	0.33

TABLE 3.2.3.0(e_1). *Design Mechanical and Physical Properties of Clad 2024 Aluminum Alloy Sheet and Plate*

Specification	QQ-A-250/5																			
Form	Flat sheet and plate																			
Temper	T3								T351											
Thickness, in.	0.008-0.009		0.010-0.062		0.063-0.128		0.129-0.249		0.250-0.499		0.500-1.000[a]		1.001-1.500[a]		1.501-2.000[a]		2.001-3.000[a]		3.001-4.000[a]	
Basis	A	B	A	B	A	B	A	B	A	B	A	B	A	B	A	B	A	B	A	B
Mechanical Properties:																				
F_{tu}, ksi:																				
L	59	60	60	61	62	63	63	64	62	64	61	63	60	62	60	62	58	60	55	57
LT	58	59	59	60	61	62	62	63	62	64	61	63	60	62	60	62	58	60	55	57
ST	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	52	54	49	51
F_{ty}, ksi:																				
L	44	45	44	45	45	47	45	47	46	48	45	48	45	48	45	47	44	46	39	41
LT	39	40	39	40	40	42	40	42	40	42	40	42	40	42	40	42	40	42	39	41
ST	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	38	40	38	39
F_{cy}, ksi:																				
L	36	37	36	37	37	39	37	39	37	39	37	39	37	39	36	38	35	37	33	35
LT	42	43	42	43	43	45	43	45	43	45	42	45	42	44	42	44	41	43	39	41
ST	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	46	48	44	47
F_{su}, ksi	37	37	37	38	38	39	39	40	37	38	36	37	35	37	35	37	34	35	32	34
F_{bru}[b], ksi:																				
(e/D = 1.5)	96	97	97	99	101	102	102	104	94	97	92	95	91	94	91	94	88	91	83	86
(e/D = 2.0)	119	121	121	123	125	127	127	129	115	119	113	117	111	115	111	115	107	111	102	106
F_{bry}[b], ksi:																				
(e/D = 1.5)	68	70	68	70	70	73	70	73	69	72	69	72	69	72	69	72	69	72	67	70
(e/D = 2.0)	82	84	82	84	84	88	84	88	82	86	82	86	82	86	82	86	82	86	80	84
e, percent (S-basis):																				
LT	10	...	c	...	15	...	15	...	12	...	8	...	7	...	6	...	4	...	4	...
E, 10^3 ksi:																				
Primary	10.5								10.7											
Secondary	9.5				10.0				10.2											
E_c, 10^3 ksi:																				
Primary	10.7								10.9											
Secondary	9.7				10.2				10.4											
G, 10^3 ksi	...																			
μ	0.33																			
Physical Properties:																				
ω, lb/in.^{3}	0.101																			
C, K, and α	...																			

[a]These values, except in the ST direction, have been adjusted to represent the average properties across the whole section, including the 2-½ percent nominal cladding thickness.
[b]Bearing values are "dry pin" values per Section 1.4.7.1. See Table 3.1.2.1.1.
[c]See Table 3.2.3.0(f).

TABLE 3.2.3.0(e_2). *Design Mechanical and Physical Properties of Clad 2024 Aluminum Alloy Sheet and Plate—Continued*

Specification	QQ-A-250/5							
Form	Flat sheet and plate				Coiled sheet			
Temper	T361				T4			
Thickness, in.	0.020-0.062	0.063-0.249	0.250-0.499	0.500[a]	0.010-0.062		0.063-0.128	
Basis	S	S	S	S	A	B	A	B
Mechanical Properties:								
F_{tu}, ksi:								
L	62	65	65	64	58	59	61	62
LT	61	64	64	63	58	59	61	62
F_{ty}, ksi:								
L	53	53	53	52	36	38	38	39
LT	47	48	48	47	36	38	38	39
F_{cy}, ksi:								
L	44	45	45	44	36	38	38	39
LT	50	51	51	50	36	38	38	39
F_{su}, ksi	38	40	40	39	37	37	38	39
F_{bru}[b], ksi:								
(e/D = 1.5)	101	105	105	104	96	97	101	102
(e/D = 2.0)	125	131	131	129	119	121	125	127
F_{bry}[b], ksi:								
(e/D = 1.5)	78	79	79	78	63	66	66	68
(e/D = 2.0)	92	94	94	92	76	80	80	82
e, percent (S-basis):								
LT	8	9	9	10	[c]	...	15	...
E, 10^3 ksi:								
Primary	10.5	10.5	10.7		10.5		10.5	
Secondary	9.5	10.0	10.2		9.5		10.0	
E_c, 10^3 ksi:								
Primary	10.7	10.7	10.9		10.7		10.7	
Secondary	9.7	10.2	10.4		9.7		10.2	
G, 10^3 ksi	...							
μ	0.33							
Physical Properties:								
ω, lb/in.^{3}	0.101							
C, K, and α	...							

[a]These values have been adjusted to represent the average properties across the whole section, including the 2-½ percent nominal cladding thickness.

[b]Bearing values are "dry pin" values per Section 1.4.7.1.

[c]See Table 3.2.3.0(f).

TABLE 3.2.3.0(e_3). *Design Mechanical and Physical Properties of Clad 2024 Aluminum Alloy Sheet and Plate—Continued*

Specification	QQ-A-250/5														
Form	Flat sheet and plate														
Temper	T42[a]										T62[a]			T72[a]	
Thickness, in.	0.008-0.009		0.010-0.062		0.063-0.249		0.250-0.499	0.500-1.000[b]	1.001-2.000[b]	2.001-3.000[b]	0.010-0.062	0.063-0.249	0.250-0.499	0.010-0.062	0.063-0.249
Basis	A	B	A	B	A[c]	B[c]	S[c]	S[c]	S[c,d]	S	S	S[c]	S[c]	S	S
Mechanical Properties:															
F_{tu}, ksi:															
L	...	...	...	...	60	62	60	59	58	...	...	62	62	...	...
LT	55	57	...	59	60	62	60	59	58	56	60	62	62	56	58
F_{ty}, ksi:															
L	...	...	...	...	36	39	36	36	36	...	...	49	49	...	...
LT	34	35	34	35	36	38	36	36	36	36	47	49	49	43	45
F_{cy}, ksi:															
L	...	...	...	...	40	42	39	37	33	...	...	50	50	...	...
LT	...	...	...	...	39	41	39	39	39	...	...	51	51	...	...
F_{su}, ksi	...	...	...	...	40	41	39	36	29	...	...	39	39	...	...
F_{bru}, ksi:															
(e/D = 1.5)	...	...	...	...	95	99	94	88	78	...	...	100	100	...	...
(e/D = 2.0)	...	...	...	...	120	124	117	109	93	...	...	130	129	...	...
F_{bry}, ksi:															
(e/D = 1.5)	...	...	...	...	64	67	64	64	64	...	...	79	79	...	...
(e/D = 2.0)	...	...	...	...	74	78	74	74	74	...	...	92	92	...	...
e, percent (S-basis):															
LT	10	...	e	...	15	...	12	8	e	4	5	5	5	5	5
E, 10^3 ksi:															
Primary	10.5				10.5		10.7					10.5	10.7	10.5	10.5
Secondary	9.5				10.0		10.2					10.0	10.2	9.5	10.0
E_c, 10^3 ksi:															
Primary	10.7				10.7		10.9					10.7	10.9	10.7	10.7
Secondary	9.7				10.2		10.4					10.2	10.4	9.7	10.2
G, 10^3 ksi	...														
μ	0.33														
Physical Properties:															
ω, lb/in.^{3}	0.101														
C, K, and α	...														

[a] Design allowables in some cases were based upon data obtained from testing samples of material, supplied in the O or F temper, which were heat treated to demonstrate response to heat treatment by suppliers. Properties obtained by the user may be different than those listed if the material has been formed or otherwise cold or hot worked, particularly in the annealed temper, prior to solution heat treatment.
[b] These values, except in the ST direction, have been adjusted to represent the average properties across the whole section, including 2½ percent per side nominal cladding thickness.
[c] Bearing values are "dry pin" values per Section 1.4.7.1.
[d] See Table 3.1.2.1.1.
[e] See Table 3.2.3.0(f).

TABLE 3.2.3.0(e_4). *Design Mechanical and Physical Properties of Clad 2024 Aluminum Alloy Sheet and Plate—Continued*

Specification	QQ-A-250/5								
Form	Flat sheet and plate								
Temper	T81		T851[a]			T861[a]			
Thickness, in.	0.010-0.062	0.063-0.249	0.250-0.499		0.500-1.000[b]	0.020-0.062	0.063-0.249	0.250-0.499	0.500[b]
Basis	S	S	A	B	S	S	S	S	S
Mechanical Properties:									
F_{tu}, ksi:									
L	64	67	65	66	63	65	70	68	67
LT	62	65	65	66	63	64	69	68	67
F_{ty}, ksi:									
L	57	59	56	58	56	59	65	62	61
LT	54	56	56	58	56	58	64	62	61
F_{cy}, ksi:									
L	55	57	56	58	56	59	65	62	61
LT	55	57	57	59	56	61	67	65	64
F_{su}, ksi	38	39	37	37	36	36	39	39	38
F_{bru}, ksi:									
(e/D = 1.5)	96	100	99	100	96	99	107	105	104
(e/D = 2.0)	122	127	127	129	123	128	138	136	134
F_{bry}, ksi:									
(e/D = 1.5)	78	83	83	86	83	84	93	90	88
(e/D = 2.0)	90	94	98	101	98	99	109	105	104
e, percent (S-basis):									
LT	5	5	5	...	5	3	4	4	4
E, 10^3 ksi:									
Primary	10.5	10.5	10.7			10.5	10.5	10.5	
Secondary	9.5	10.0	10.2			9.5	10.0	10.2	
E_c, 10^3 ksi:									
Primary	10.7	10.7	10.9			10.7	10.7	10.9	
Secondary	9.7	10.2	10.4			9.7	10.2	10.4	
G, 10^3 ksi	...								
μ	0.33								
Physical Properties:									
ω, lb/in.^{3}	0.101								
C, K, and α	...								

[a]Bearing values are "dry pin" values per Section 1.4.7.1.

[b]These values have been adjusted to represent the average properties across the whole section, including the 2-½ percent nominal cladding thickness.

TABLE 3.2.3.0(f). *Minimum Elongation Values for Clad 2024 Aluminum Alloy Sheet and Plate*

	Elongation (LT), percent
Temper	T3, T4, T42
Thickness, in.:	
0.010-0.020	12
0.021-0.062	15
1.001-1.500	7
1.501-2.000	6

TABLE 3.2.3.0(g). *Design Mechanical and Physical Properties of 2024 Aluminum Alloy Drawn Tubing*

Specification	AMS 4086 and WW-T-700/3		WW-T-700/3	
Form	Drawn tubing			
Temper	T3		T42[a]	T81
Wall thickness, in.	0.018-0.500		0.018-0.500	0.010-0.249
Basis	A	B	S	S
Mechanical Properties:				
F_{tu}, ksi:				
L	64	66	62	66
LT	...	...	...	...
F_{ty}, ksi:				
L	42	45	38	58
LT	...	...	...	...
F_{cy}, ksi:				
L	42	45	38	...
LT	...	...	...	...
F_{su}, ksi	39	40	38	...
F_{bru}, ksi:				
(e/D = 1.5)	96	99	93	...
(e/D = 2.0)	122	126	118	...
F_{bry}, ksi:				
(e/D = 1.5)	59	63	53	...
(e/D = 2.0)	67	72	61	...
e, percent (S-basis):				
L	b	...	b	b
E, 10^3 ksi	10.5			
E_c, 10^3 ksi	10.7			
G, 10^3 ksi	4.0			
μ	0.33			
Physical Properties:				
ω, lb/in.^{3}	0.101			
C, K, and α	See Figure 3.2.3.0			

[a]Design allowables were based upon data obtained from testing samples of material supplied in the O or F temper, which were heat treated to demonstrate response to heat treatment by suppliers. Properties obtained by the user, however, may be lower than those listed if the material has been formed or otherwise cold or hot worked, particularly in the annealed temper, prior to solution heat treatment.

[b]See Table 3.2.3.0(h).

TABLE 3.2.3.0(h). *Minimum Elongation Values for 2024 Aluminum Alloy Drawn Tubing*

	Elongation (L), percent[a]
Temper	T3, T42
Wall Thickness, in.:	
0.018-0.024	10
0.025-0.049	12
0.050-0.259	14
0.260-0.500	16
Temper	T81
0.010-0.024	...
0.025-0.049	5
0.050-0.249	6

[a]Full section specimen.

TABLE 3.2.3.0(i$_1$). *Design Mechanical and Physical Properties of 2024 Aluminum Alloy Bar and Rod; Rolled, Drawn, or Cold-Finished*

Specification	AMS 4120 and QQ-A-225/6							QQ-A-225/6
Form	Bar and rod; rolled, drawn, or cold-finished							
Temper	T351							T36
Thickness, in.	0.500-1.000	1.001-2.000	2.001-3.000	3.001-4.000	4.001-5.000[a]	5.001-6.000[a]	6.001-6.500[a]	≤0.375
Basis	S	S	S	S	S	S	S	S
Mechanical Properties:								
F_{tu}, ksi:								
L	62	62	62	62	62	62	62	69
LT	61	59	57	55	54	52	...	...
F_{ty}, ksi:								
L	45	45	45	45	45	45	45	52
LT	36	36	36	36	36	36	...	...
F_{cy}, ksi:								
L	34	34	34	34	34	34	...	...
LT	41	41	41	41	41	41	...	...
F_{su}, ksi	37	37	37	37	37	37	...	...
F_{bru}, ksi:								
(e/D = 1.5)	90	90	90	90	90	90	...	...
(e/D = 2.0)	115	115	115	115	115	115	...	...
F_{bry}, ksi:								
(e/D = 1.5)	63	63	63	63	63	63	...	...
(e/D = 2.0)	74	74	74	74	74	74	...	...
e, percent:								
L	10	10	10	10	10	10	10	10
E, 10^3 ksi	10.5							
E_c, 10^3 ksi	10.7							
G, 10^3 ksi	4.0							
μ	0.33							
Physical Properties:								
ω, lb/in.^{3}	0.101							
C, K, and α	See Figure 3.2.3.0							

[a]For square, rectangular, hexagonal, or octagonal bar, minimum thickness is 4 inches, and maximum cross-sectional area is 36 square inches.

TABLE 3.2.3.0(i_2). *Design Mechanical and Physical Properties of 2024 Aluminum Alloy Bar and Rod; Rolled, Drawn, or Cold-Finished—Continued*

Specification	AMS 4120 and QQ-A-225/6										QQ-A-225/6
Form	Bar and rod; rolled, drawn, or cold-finished										
Temper	T4[d]										T42[a]
Thickness, in.	0.125-0.449	0.500-1.000	1.001-2.000	2.001-3.000	3.001-4.000	4.001-4.500[b]	4.501-5.000[c]	5.001-6.000[c]	6.001-6.500[c]	6.501-8.000[c]	≤6.500[b]
Basis	S	S	S	S	S	S	S	S	S	S	S
Mechanical Properties:											
F_{tu}, ksi:											
L	62	62	62	62	62	62	62	62	62	58	62
LT	61	61	59	57	55	54	54	52	...	...	...
F_{ty}, ksi:											
L	45	42	42	42	42	42	40	40	40	38	40
LT	45	42	41	40	39	39	37	36	...	...	...
F_{cy}, ksi:											
L	36	33	33	33	33	33	32	32	...	...	...
LT	...	...	...	...	...	...	...	...	...	...	...
F_{su}, ksi	37	37	37	37	37	37	37	37	37	...	...
F_{bru}, ksi:											
(e/D = 1.5)	93	93	93	93	93	93	93	93	...	...	...
(e/D = 2.0)	118	118	118	115	118	118	118	118	...	...	...
F_{bry}, ksi:											
(e/D = 1.5)	63	59	59	59	59	59	56	56	...	...	...
(e/D = 2.0)	72	67	67	67	67	67	64	64	...	...	...
e, percent:											
L	10	10	10	10	10	10	10	10	10	10	10
E, 10^3 ksi	10.5										
E_c, 10^3 ksi	10.7										
G, 10^3 ksi	4.0										
μ	0.33										
Physical Properties:											
ω, lb/in.^{3}	0.101										
C and α	See Figure 3.2.3.0										
K, Btu/[(hr)(ft^2)(F)/ft]	71 (at 77 F) for T4X (See Figure 3.2.3.0)										

[a]These properties apply when samples of material supplied in the O or F temper are heat treated to demonstrate response to heat treatment. Properties obtained by the user, however, may be lower than those listed if the material has been formed or otherwise cold or hot worked, particularly in the annealed temper, prior to solution heat treatment.
[b]For square, rectangular, hexagonal, or octagonal bar, maximum thickness is 4 inches, and maximum cross-sectional area is 36 square inches.
[c]Applies to rod only.
[d]The T4 temper is obsolete and should not be specified for new designs.

TABLE 3.2.3.0(i_3). *Design Mechanical and Physical Properties of 2024 Aluminum Alloy Bar and Rod; Rolled, Drawn, or Cold-Finished—Continued*

Specification	QQ-A-225/6		
Form	Bar and rod; rolled, drawn, or cold finished		
Temper	T6[a]	T62[b]	T851
Thickness,[c] in.	≤6.500	≤6.500	0.500-6.500
Basis	S	S	S
Mechanical Properties:			
F_{tu}, ksi:			
L	62	60	66
LT	...	...	...
F_{ty}, ksi:			
L	50	46	58
LT	...	...	...
F_{cy}, ksi:			
L	...	...	...
LT	...	...	...
F_{su}, ksi	...	...	...
F_{bru}, ksi:			
(e/D = 1.5)	...	...	...
(e/D = 2.0)	...	...	...
F_{bry}, ksi:			
(e/D = 1.5)	...	...	...
(e/D = 2.0)	...	...	...
e, percent:			
L	5	5	5
E, 10^3 ksi	10.5		
E_c, 10^3 ksi	10.7		
G, 10^3 ksi	4.0		
μ	0.33		
Physical Properties:			
ω, lb/in.^{3}	0.101		
C and α	See Figure 3.2.3.0		
K, Btu/[(hr)(ft^2)(F)/ft]	87 (at 77 F) for T6X and T8XX		

[a]The T6 temper is obsolete and should not be specified for new designs.

[b]These properties apply when samples of material supplied in the O or F temper are heat treated to demonstrate response to heat treatment. Properties obtained by the user, however, may be lower than those listed if the material has been formed or otherwise cold or hot worked, particularly in the annealed temper, prior to solution heat treatment.

[c]For square, rectangular, hexagonal, or octagonal bar, maximum thickness is 4 inches, and maximum cross-sectional area is 36 square inches.

TABLE 3.2.3.0(j$_1$). *Design Mechanical and Physical Properties of 2024 Aluminum Alloy Extrusion*

Specification	AMS 4152, AMS 4164, AMS 4165, and QQ-A-200/3														QQ-A-200/3		
Form	Extruded bar, rod, and shapes																
Temper	T3, T3510, and T3511														T81, T8510, and T8511		
Thickness, in.	≤0.249		0.250-0.499		0.500-0.749		0.750-1.499		1.500-2.999		3.000-4.499		1.500-2.999	3.000-4.499	0.050-0.249	0.250-1.499	1.500-4.500
Cross-section area, in.^{2}	≤20								≤25				>25, ≤32		≤20		≤32
Basis	A	B	A	B	A	B	A	B	A	B	A	B	S	S	S	S	S
Mechanical Properties:																	
F_{tu}, ksi:																	
L	57	61	60	62	60	62	65	70	70	74	70	74	68	68	64	66	66
LT	54	58	56	57	54	56	56	60	55	58	54	57	53	52	64	64	61
F_{ty}, ksi:																	
L	42	47	44	47	44	47	46	54	52	54	52	54	48	48	56	58	58
LT	37	41	38	40	37	39	37	43	39	41	39	41	36	36	55	57	57
F_{cy}, ksi:																	
L	34	38	37	39	38	40	41	48	49	50	49	51	45	45	57	59	59
LT	41	45	41	44	40	43	40	47	42	44	41	43	39	38	57	59	59
F_{su}, ksi	29	31	31	32	30	31	33	35	34	36	33	35	33	32	35	36	36
F_{bru}[a], ksi:																	
(e/D = 1.5)	84	90	78	81	78	80	84	90	88	93	86	91	86	84	94	96	92
(e/D = 2.0)	108	114	98	101	97	101	105	113	111	118	109	115	108	106	123	123	117
F_{bry}[a], ksi:																	
(e/D = 1.5)	61	68	55	59	55	59	57	67	63	66	62	65	59	57	79	82	82
(e/D = 2.0)	71	79	67	71	67	71	69	81	77	80	75	78	71	69	93	96	96
e, percent (S-basis):																	
LT	12	...	12	...	12	...	10	...	10	...	10	...	8	8	4	5	5
E, 10^3 ksi	10.8																
E_c, 10^3 ksi	11.0																
G, 10^3 ksi	4.1																
μ	0.33																
Physical Properties:																	
ω, lb/in.^{3}	0.101																
C, K, and α	See Figure 3.2.3.0																

[a]Bearing values are "dry pin" values per Section 1.4.7.1.

TABLE 3.2.3.0(j$_2$). *Design Mechanical and Physical Properties of 2024 Aluminum Alloy Extrusion—Continued*

Specification	QQ-A-200/3									
Form	Extruded bar, rod, and shapes									
Temper	T42[a]									
Cross-sectional area, in.^{2}	≤ 25									
Thickness or diameter, in.	≤ 0.249	0.250-0.499	0.500-0.749	0.750-0.999	1.000-1.249	1.250-1.499	1.500-1.749	1.750-1.999	2.000-2.249	2.250-2.499
Basis	S	S	S	S	S	S	S	S	S	S
Mechanical Properties:										
F_{tu}, ksi:										
L	57	57	57	57	57	57	57	57	57	57
LT	55	54	52	51	49	47	45	43	41	39
F_{ty}, ksi:										
L	38	38	38	38	38	38	38	38	38	38
LT	36	35	34	33	32	31	30	29	28	27
F_{cy}, ksi:										
L	38	38	38	38	38	38	38	38	38	38
LT	39	38	37	36	35	34	33	31	30	29
F_{su}, ksi	29	29	29	29	29	29	28	27	26	24
F_{bru}[b], ksi:										
(e/D = 1.5)	81	80	79	77	75	74	71	69	67	64
(e/D = 2.0)	99	98	97	95	93	91	89	86	83	81
F_{bry}[b], ksi:										
(e/D = 1.5)	56	55	53	51	49	47	44	41	39	36
(e/D = 2.0)	69	67	65	63	61	59	56	53	50	47
e, percent:										
L	12	12	12	10	10	10	10	10	10	10
E, 10^3 ksi	10.8									
E_c, 10^3 ksi	11.0									
G, 10^3 ksi	4.1									
μ	0.33									
Physical Properties:										
ω, lb/in.^{3}	0.101									
C, K, and α	See Figure 3.2.3.0									

[a]Design allowables were based upon data obtained from testing samples of material supplied in the O or F temper, which were heat treated to demonstrate response to heat treatment by suppliers. Properties obtained by the user however, may be lower than those listed if the material has been formed or otherwise cold or hot worked, particularly in the annealed temper, prior to solution heat treatment.

[b]Bearing values are "dry pin" values per Section 1.4.7.1.

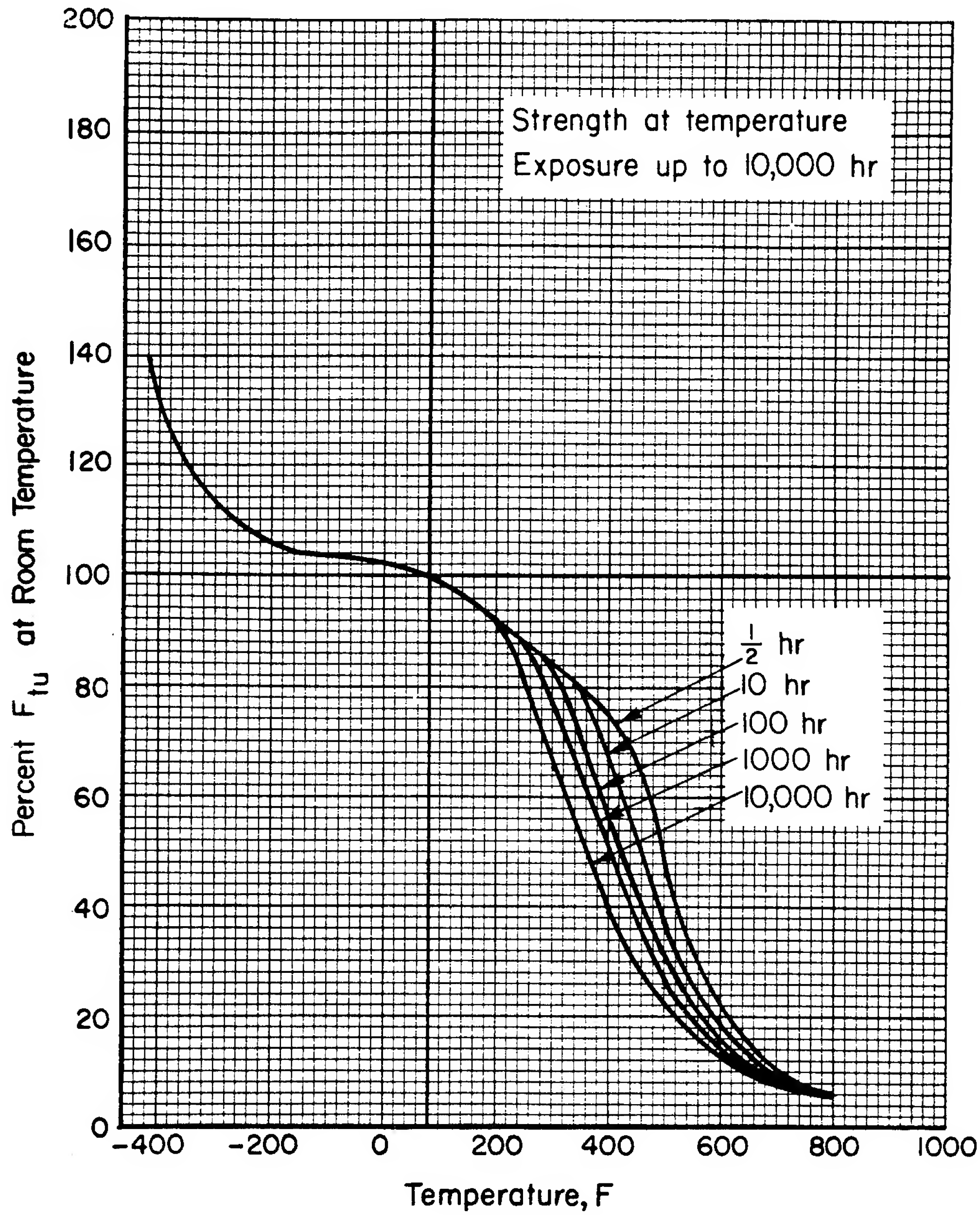

FIGURE 3.2.3.1.1(a). *Effect of temperature on the ultimate tensile strength (F_{tu}) of 2024-T3, T351, and 2024-T4 aluminum alloy (all products except extrusions).*

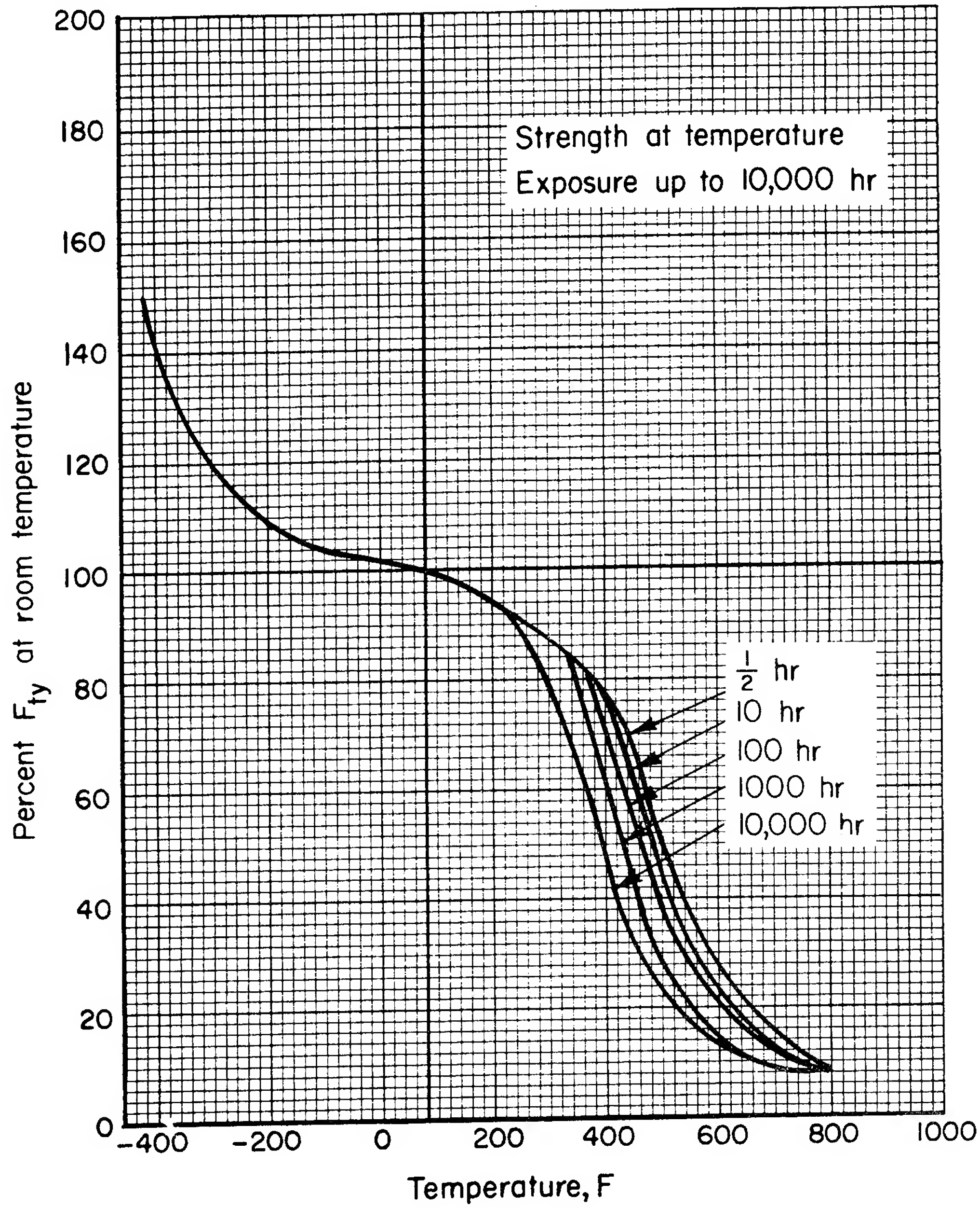

FIGURE 3.2.3.1.1(b). *Effect of temperature on the tensile yield strength (F_{ty}) of 2024-T3, T351 and 2024-T4 aluminum alloy (all products except extrusions).*

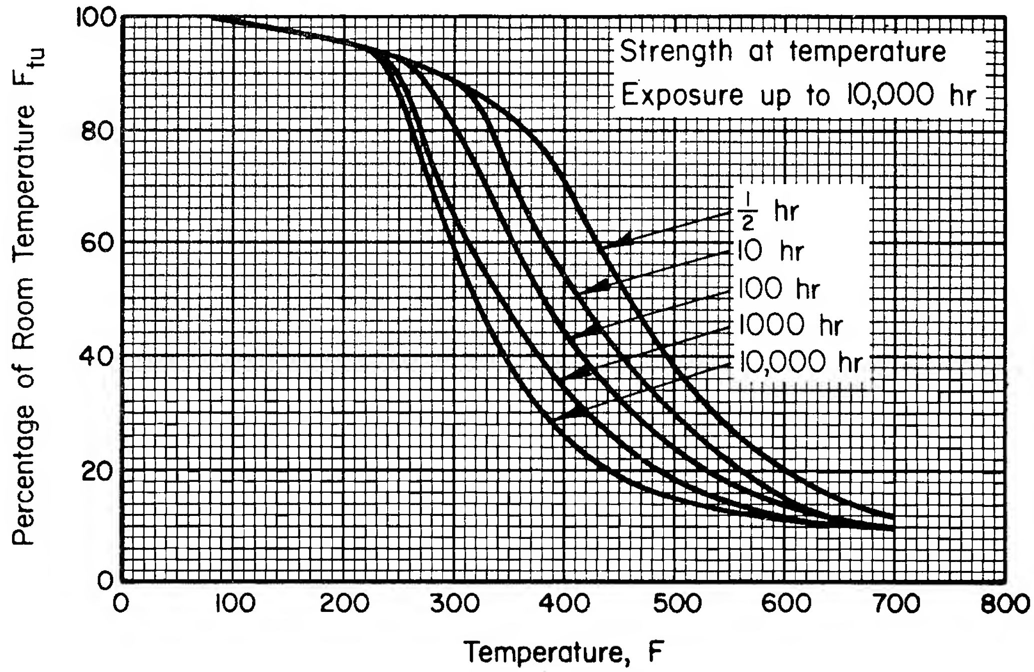

FIGURE 3.2.3.1.1(c). *Effect of temperature on the tensile ultimate strength (F_{tu}) or 2024-T3, T3510, T3511, and T42 aluminum alloy extrusion.*

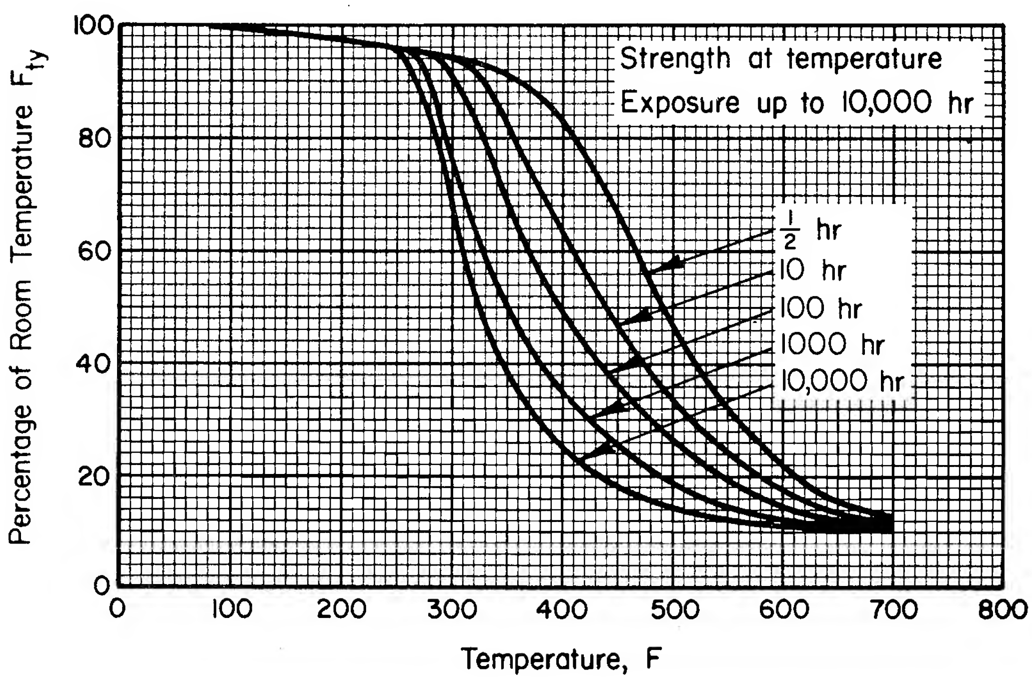

FIGURE 3.2.3.1.1(d). *Effect of temperature on the tensile yield strength (F_{ty}) of 2024-T3, T3510, T3511, and T42 aluminum alloy extrusion.*

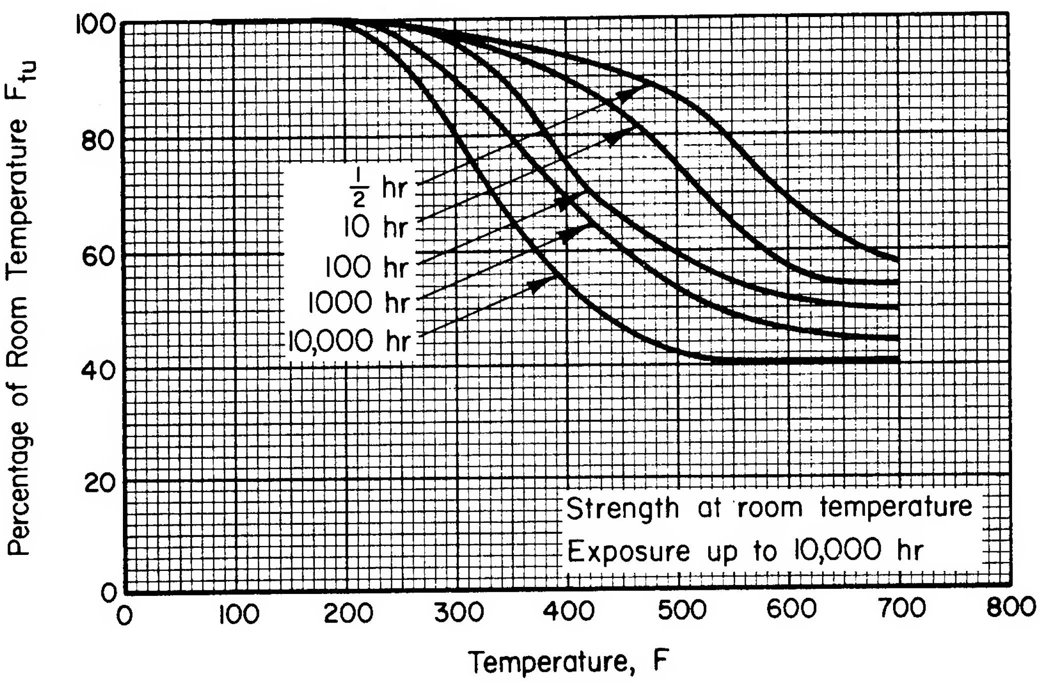

FIGURE 3.2.3.1.1(e). *Effect of exposure at elevated temperatures on the room-temperature tensile ultimate strength (F_{tu}) of 2024-T3, T351, T3510, T3511, T4, and T42 aluminum alloy (all products except thick extrusions).*

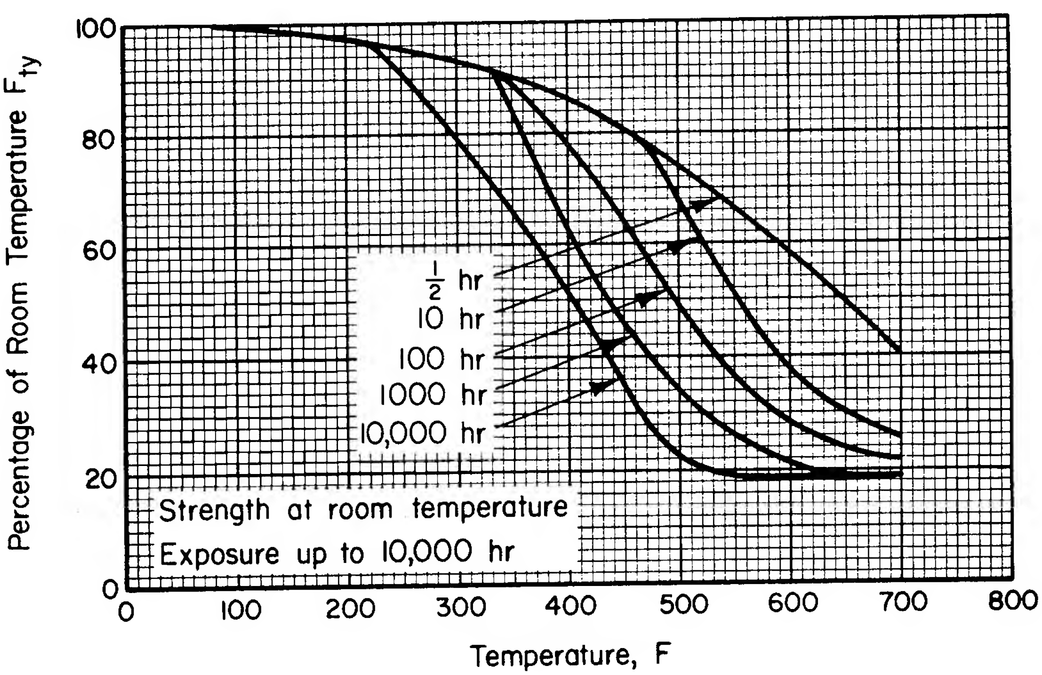

FIGURE 3.2.3.1.1(f). *Effect of exposure at elevated temperatures on the room-temperature tensile yield strength (F_{ty}) of 2024-T3, T351, T3510, T3511, T4, and T42 aluminum alloy (all products except thick extrusions).*

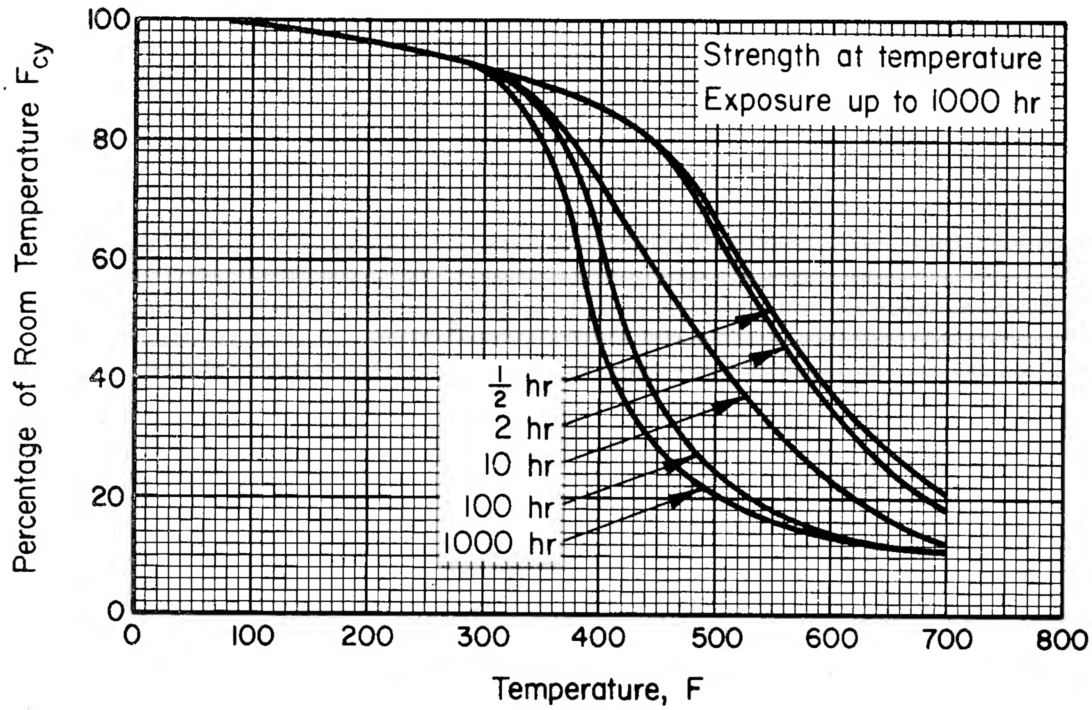

FIGURE 3.2.3.1.2(a). *Effect of temperature on the compressive yield strength (F_{cy}) of flat clad 2024-T3, coiled clad 2024-T4 aluminum alloy sheet, and clad 2024-T351 aluminum alloy plate.*

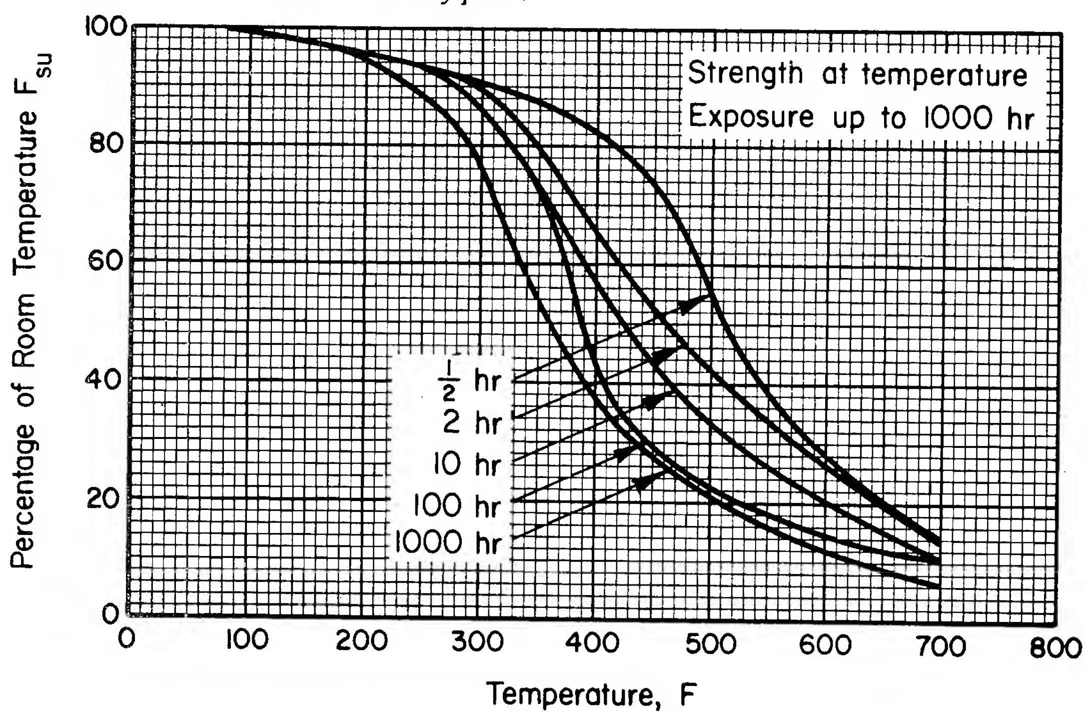

FIGURE 3.2.3.1.2(b). *Effect of temperature on the shear ultimate strength (F_{su}) of flat clad 2024-T3, coiled clad 2024-T4 aluminum alloy sheet, and clad 2024-T351 aluminum alloy plate.*

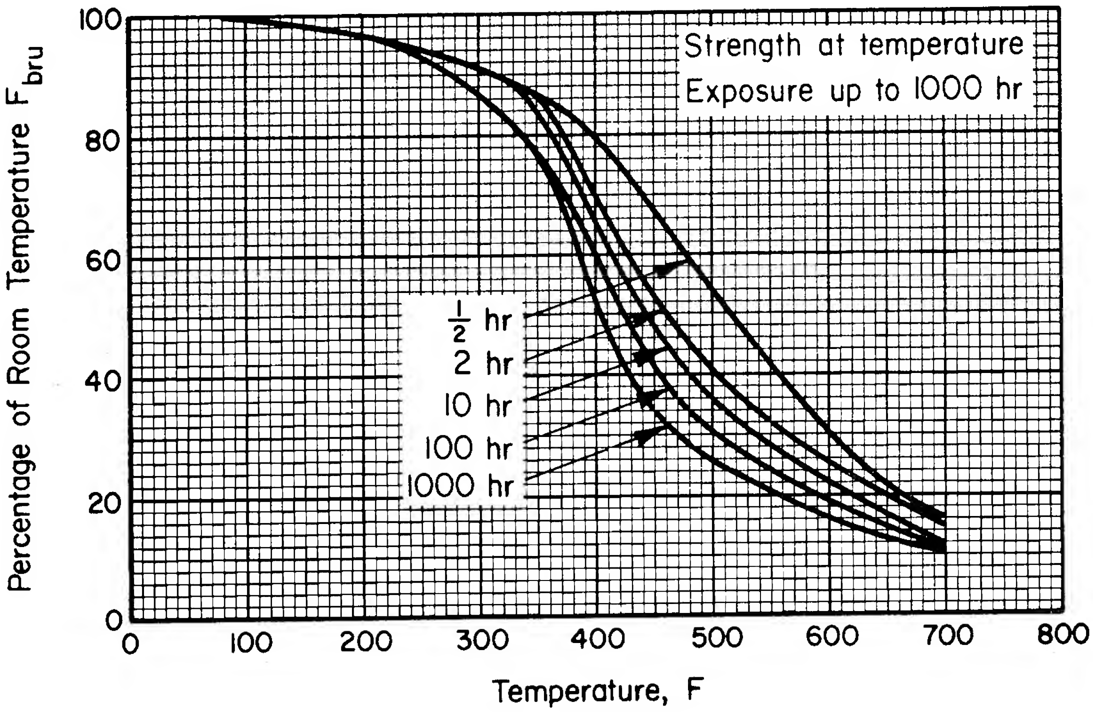

FIGURE 3.2.3.1.3(a). *Effect of temperature on the bearing ultimate strength (F_{bru}) of flat clad 2024-T3, coiled clad 2024-T4 aluminum alloy sheet, and clad 2024-T351 aluminum alloy plate.*

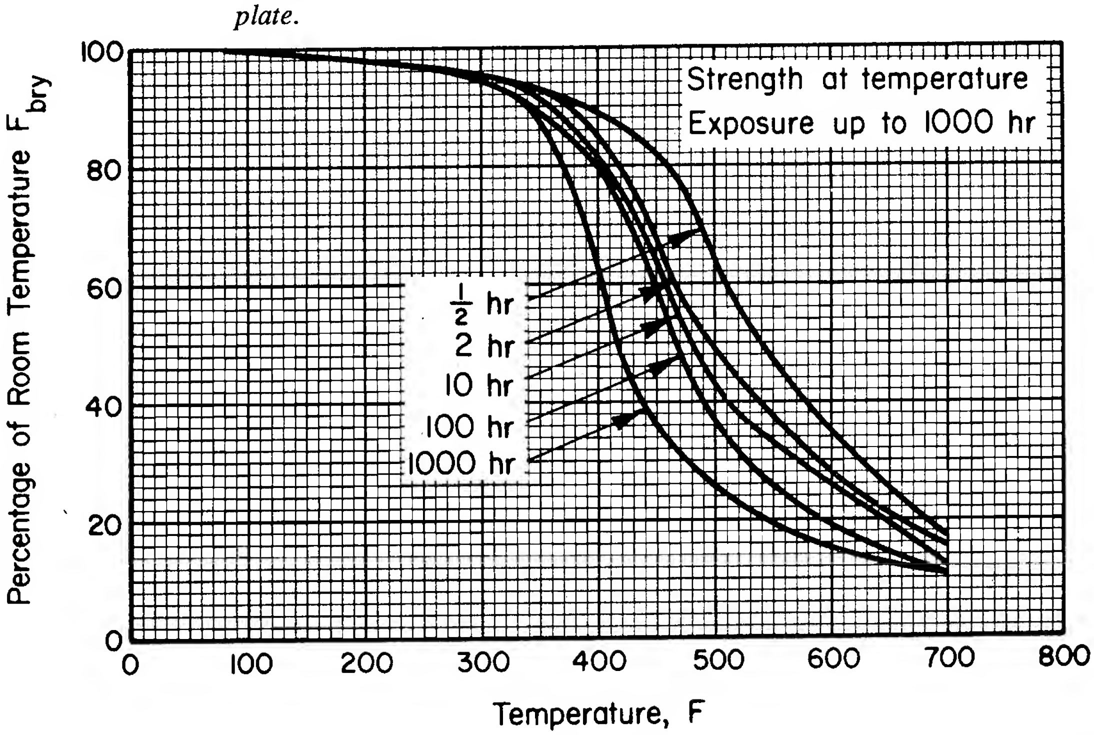

FIGURE 3.2.3.1.3(b). *Effect of temperature on the bearing yield strength (F_{bry}) of flat clad 2024-T3, coiled clad 2024-T4 aluminum alloy sheet, and clad 2024-T351 aluminum alloy plate.*

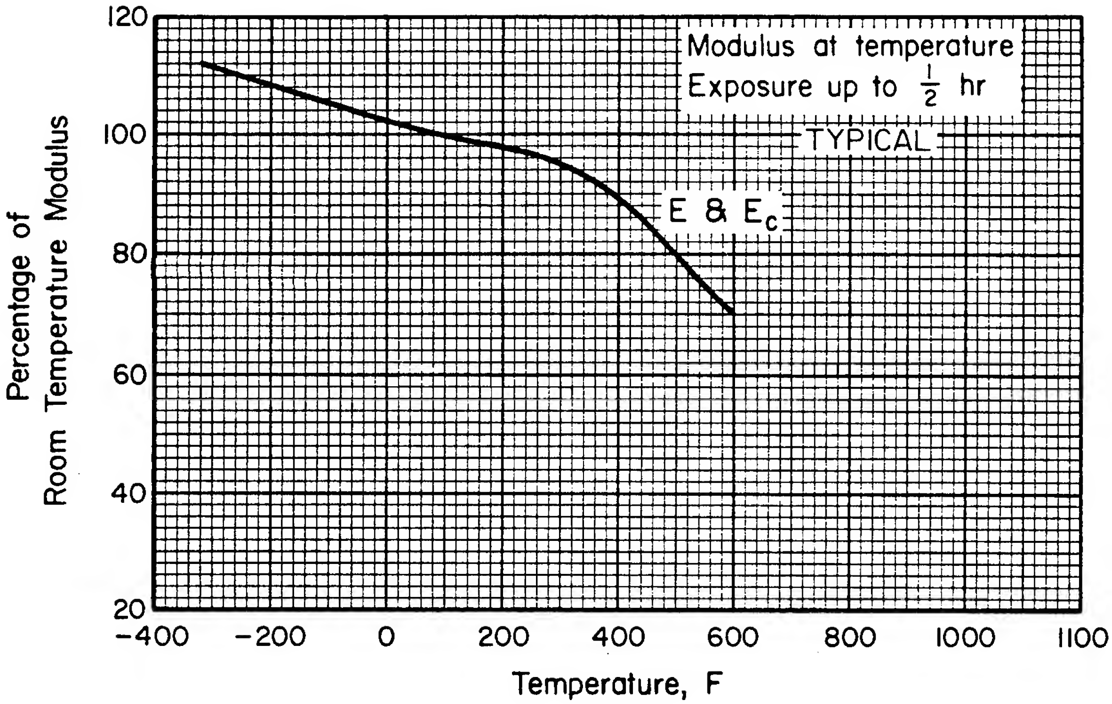

FIGURE 3.2.3.1.4. *Effect of temperature on the tensile and compressive moduli (E and E_c) of 2024 aluminum alloy.*

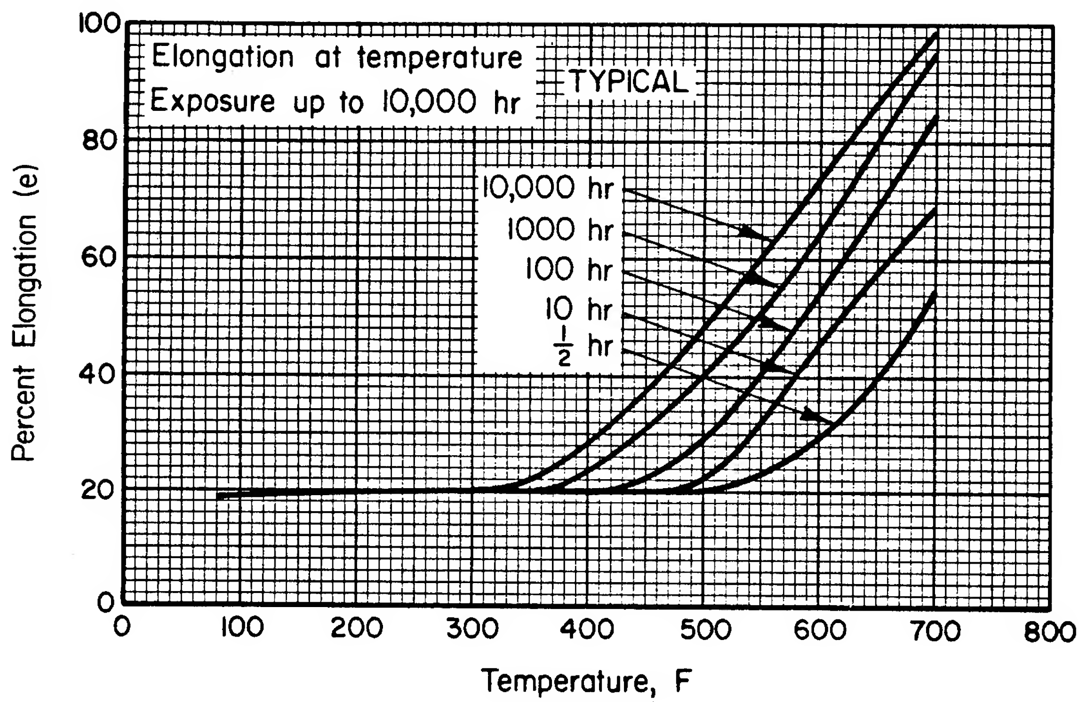

FIGURE 3.2.3.1.5(a). *Effect of temperature on the elongation of 2024-T3, T351, T3510, T3511, T4, and T42 aluminum alloy (all products except thick extrusions).*

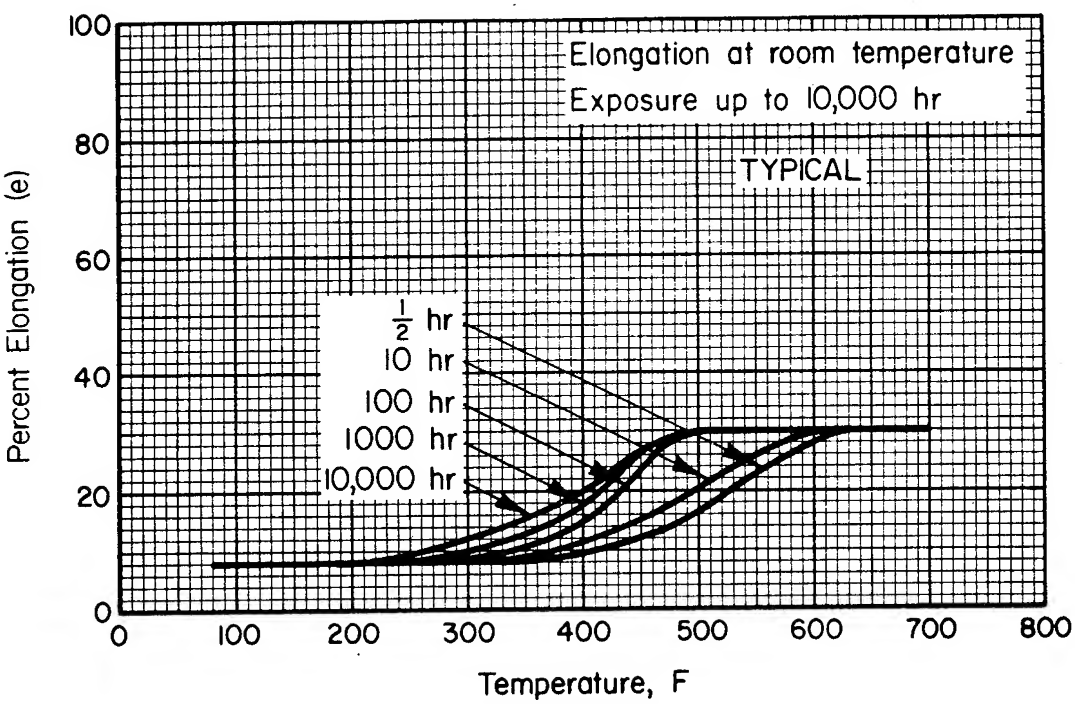

FIGURE 3.2.3.1.5(b). *Effect of exposure at elevated temperature on the elongation (e) of 2024-T3, T351, T3510, T3511, T4, and T42 aluminum alloy (all products except thick extrusions).*

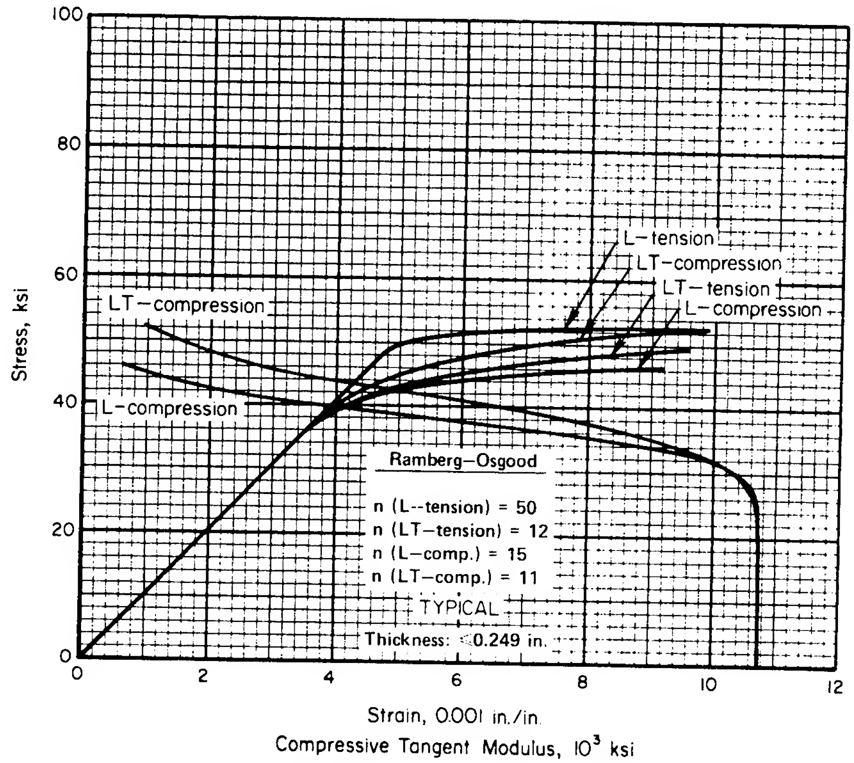

FIGURE 3.2.3.1.6(a). *Typical tensile and compressive stress-strain and compressive tangent-modulus curves for 2024-T3 aluminum alloy sheet at room temperature.*

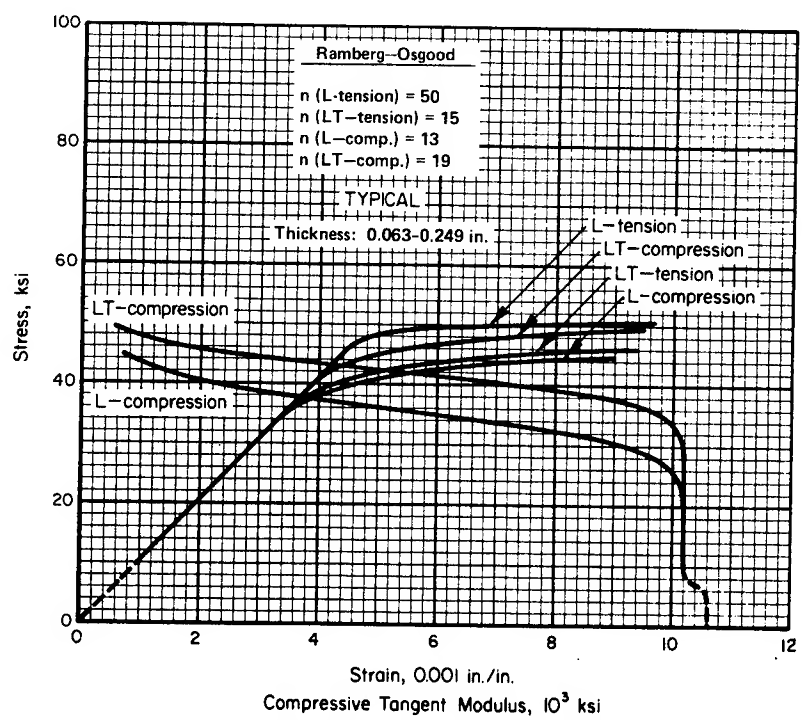

FIGURE 3.2.3.1.6(b). *Typical tensile and compressive stress-strain and compressive tangent-modulus curves for clad 2024-T3 aluminum alloy sheet at room temperature.*

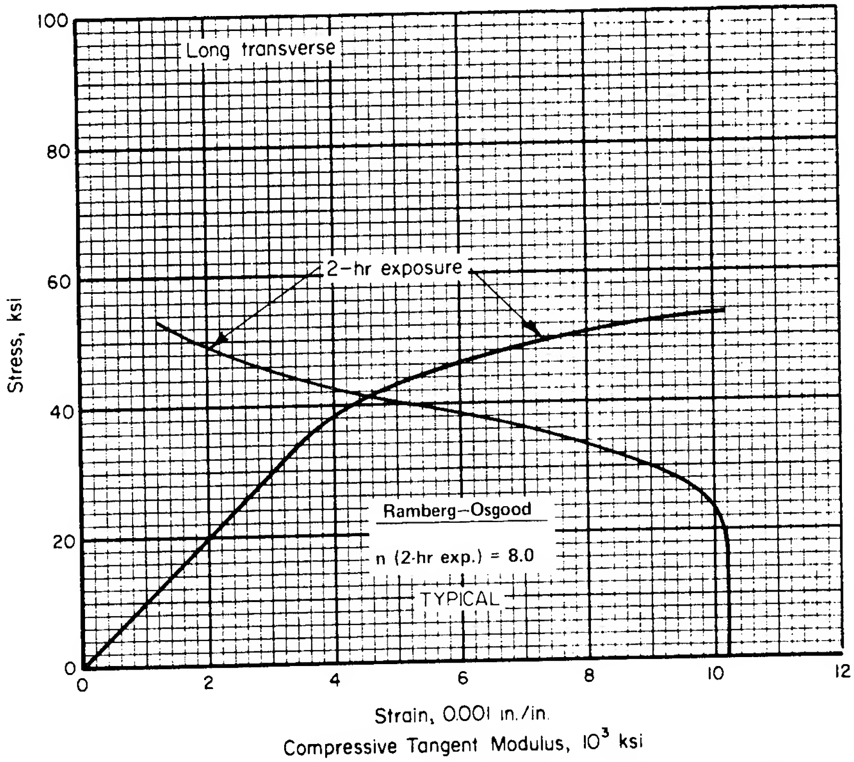

FIGURE 3.2.3.1.6(c). *Typical compressive stress-strain and compressive tangent-modulus curves for clad 2024-T3 aluminum alloy sheet at 212 F.*

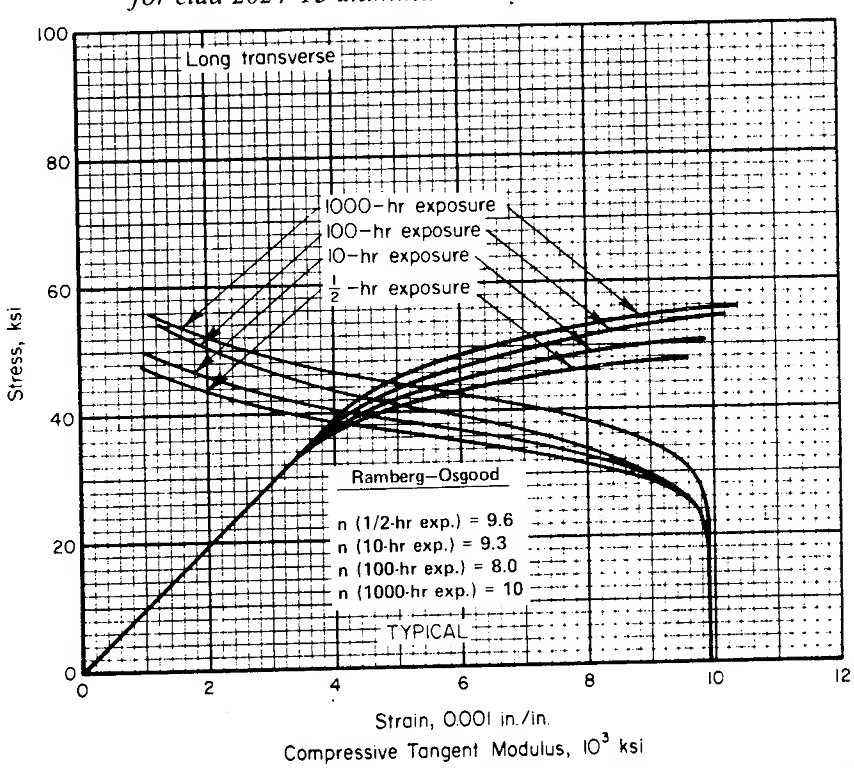

FIGURE 3.2.3.1.6(d). *Typical compressive stress-strain and compressive tangent-modulus curves for clad 2024-T3 aluminum alloy sheet at 300 F.*

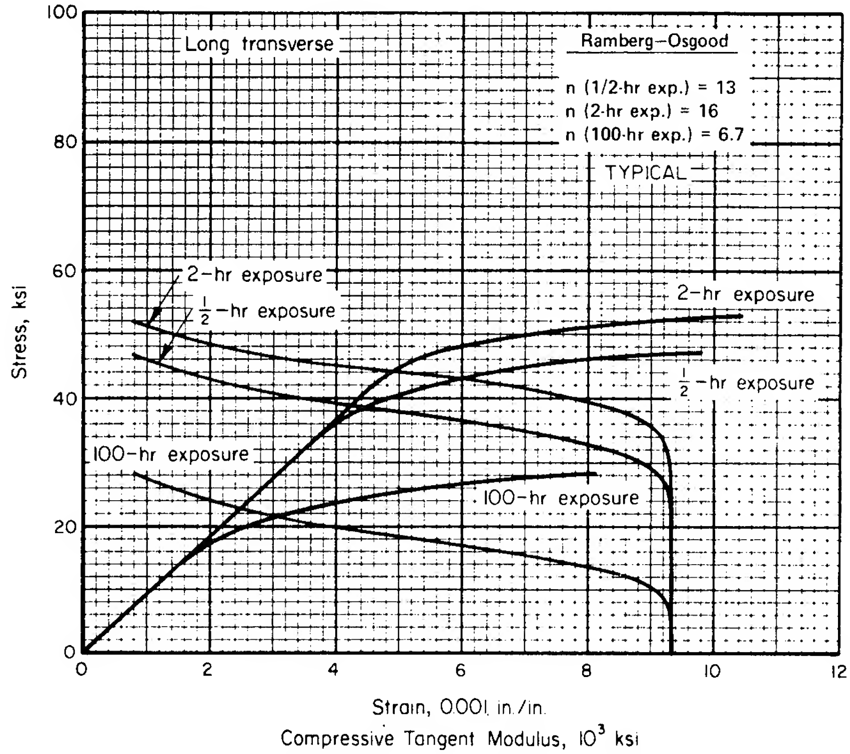

FIGURE 3.2.3.1.6(e). *Typical compressive stress-strain and compressive tangent-modulus curves for clad 2024-T3 aluminum alloy sheet at 400 F.*

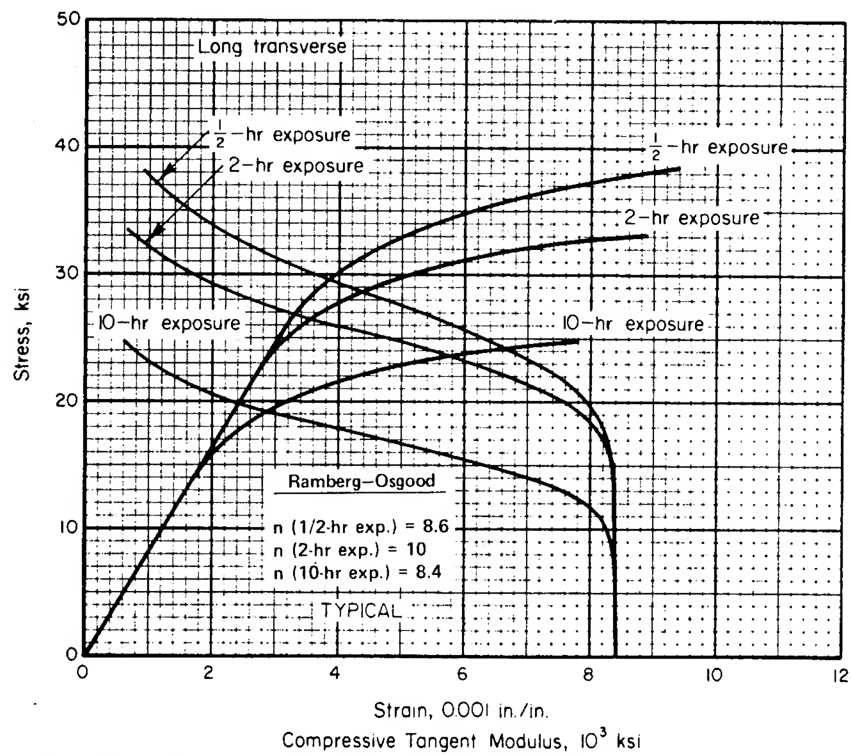

FIGURE 3.2.3.1.6(f). *Typical compressive stress-strain and compressive tangent-modulus curves for clad 2024-T3 aluminum alloy sheet at 500 F.*

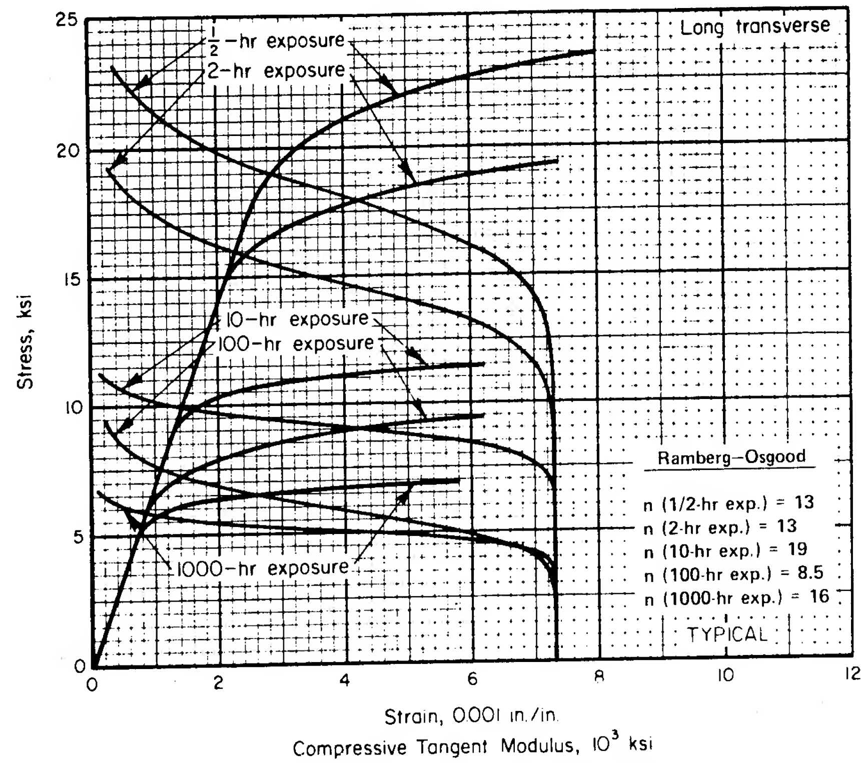

FIGURE 3.2.3.1.6(g). *Typical compressive stress-strain and compressive tangent-modulus curves for clad 2024-T3 aluminum alloy sheet at 600 F.*

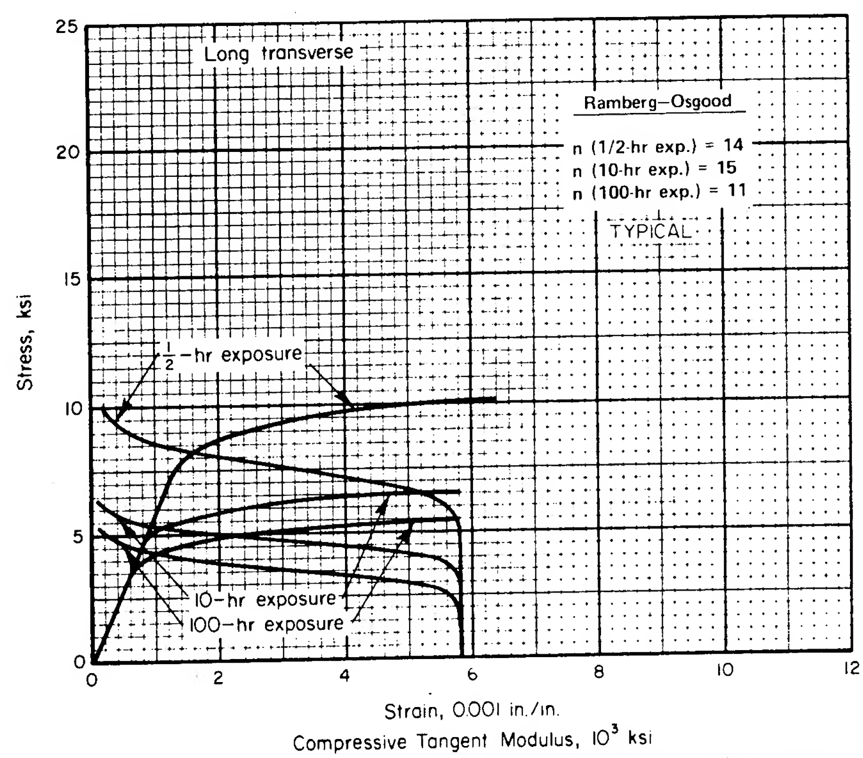

FIGURE 3.2.3.1.6(h). *Typical compressive stress-strain and compressive tangent-modulus curves for clad 2024-T3 aluminum alloy sheet at 700 F.*

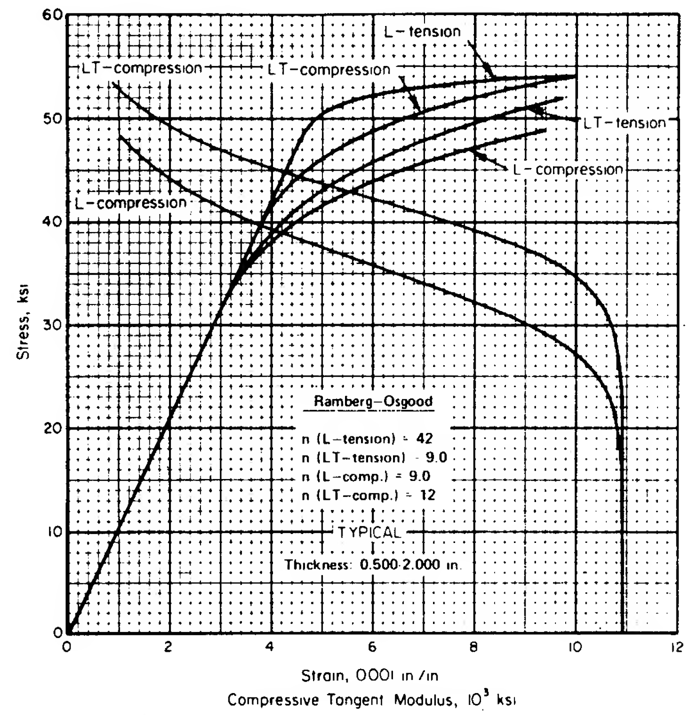

FIGURE 3.2.3.1.6(i). *Typical tensile and compressive stress-strain and compressive tangent-modulus curves for 2024-T351 aluminum alloy plate at room temperature.*

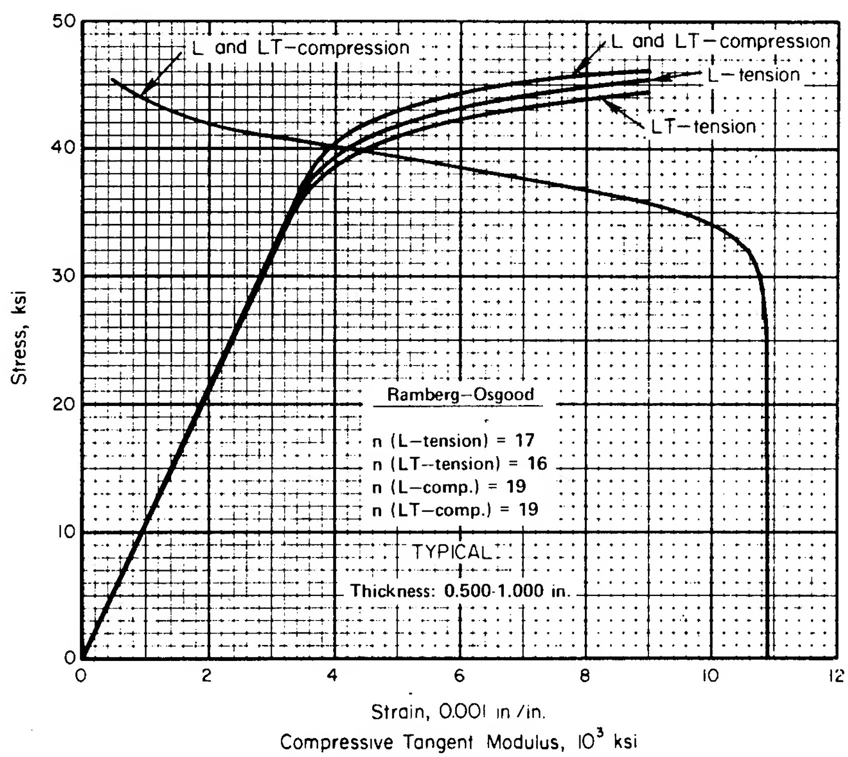

FIGURE 3.2.3.1.6(j). *Typical tensile and compressive stress-strain and compressive tangent-modulus curves for 2024-T42 aluminum alloy plate at room temperature.*

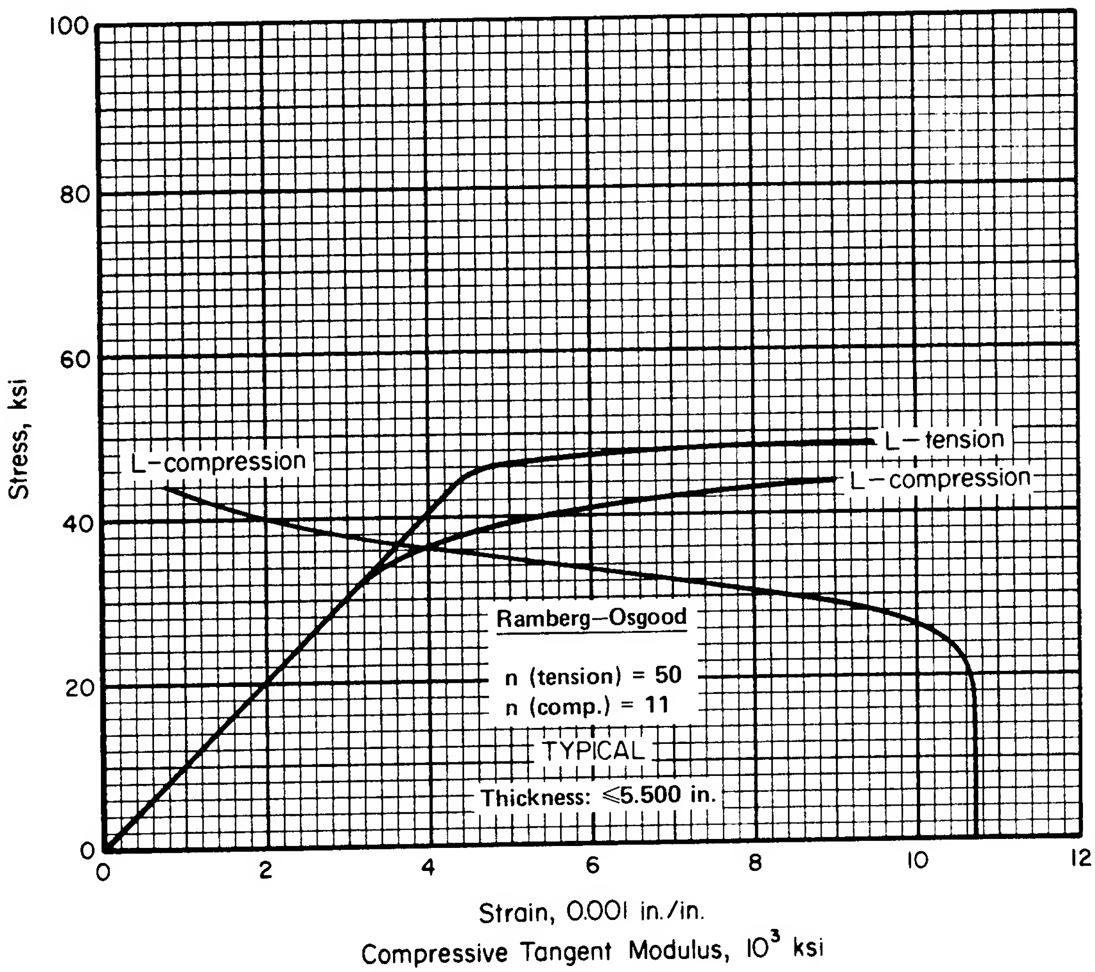

FIGURE 3.2.3.1.6(k). *Typical tensile and compressive stress-strain and compressive tangent-modulus curves for 2024-T4 aluminum alloy rolled bar, rod, and shapes at room temperature.*

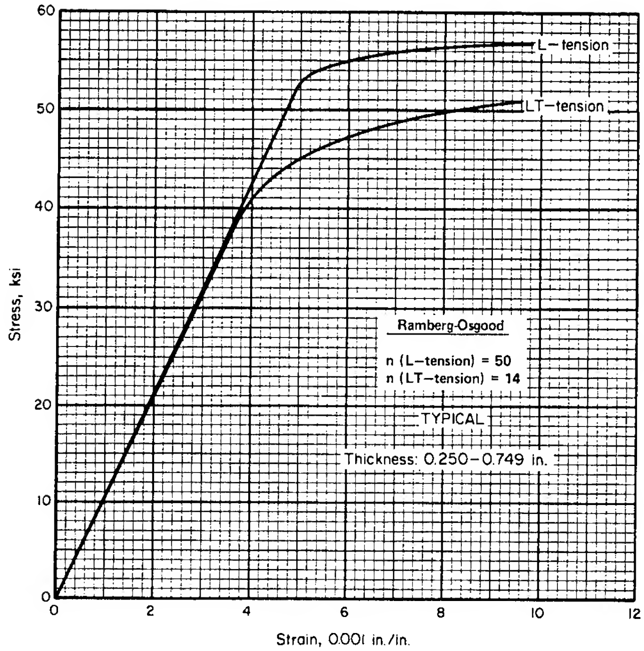

FIGURE 3.2.3.1.6(l). *Typical tensile stress-strain curves for 2024-T351X aluminum alloy extrusion at room temperature.*

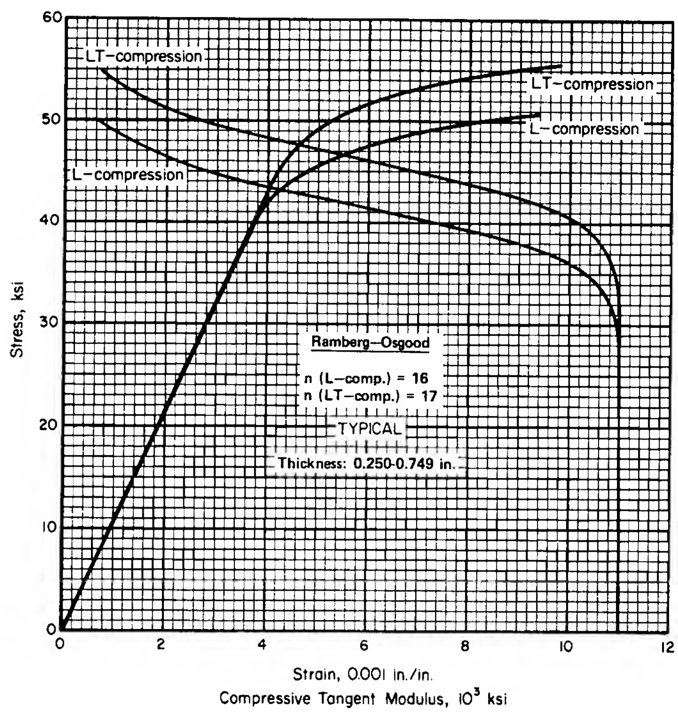

FIGURE 3.2.3.1.6(m). *Typical compressive stress-strain and compressive tangent-modulus curves for 2024-T351X aluminum alloy extrusion at room temperature.*

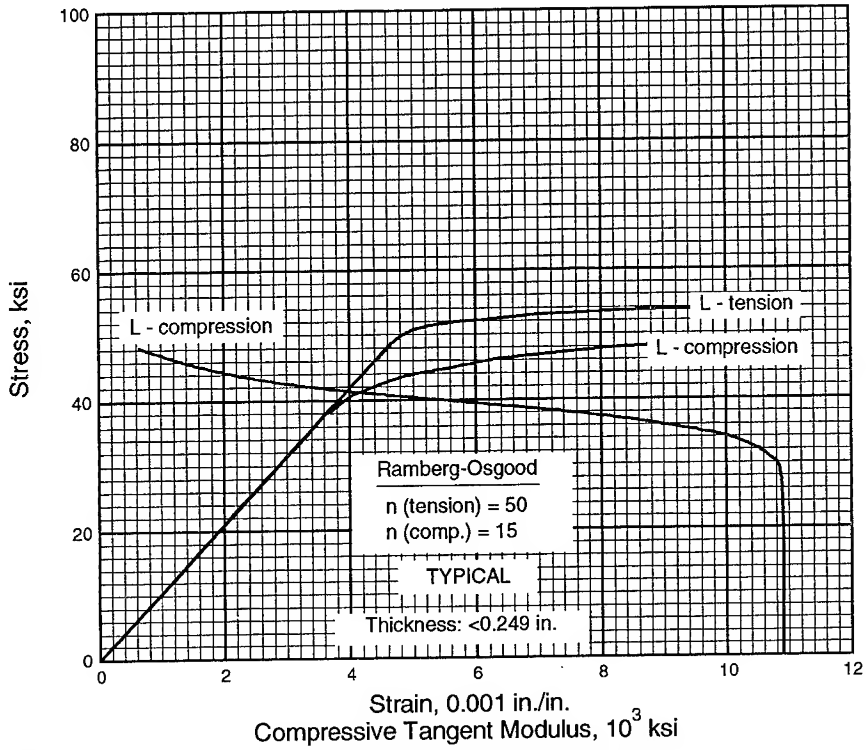

FIGURE 3.2.3.1.6(n). *Typical tensile and compressive stress-strain and compressive tangent-modulus curves for 2024-T3 aluminum alloy extrusion at room temperature.*

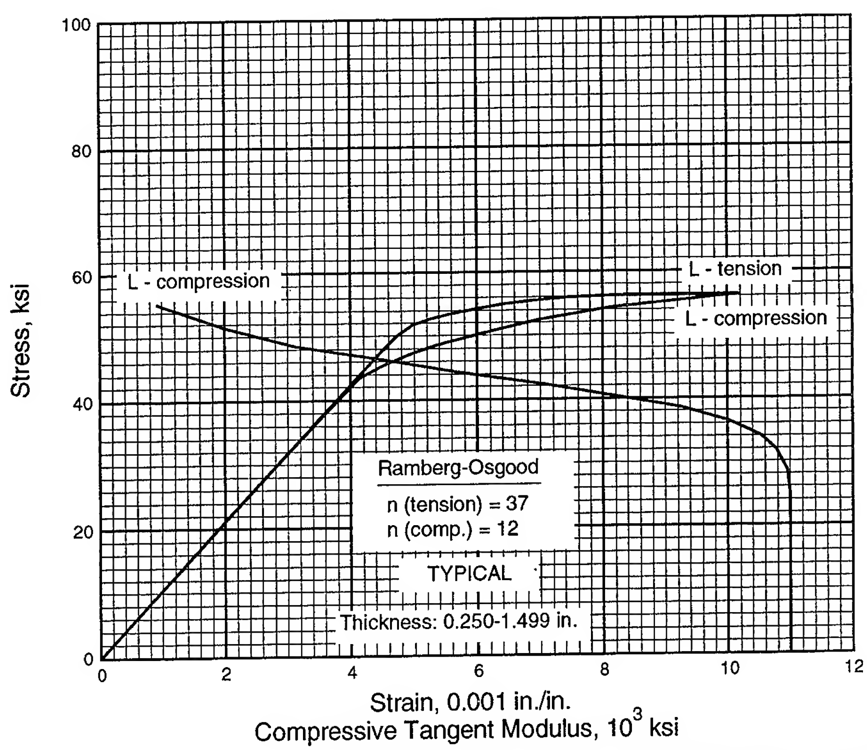

FIGURE 3.2.3.1.6(o). *Typical tensile and compressive stress-strain and compressive tangent-modulus curves for 2024-T3 aluminum alloy extrusion at room temperature.*

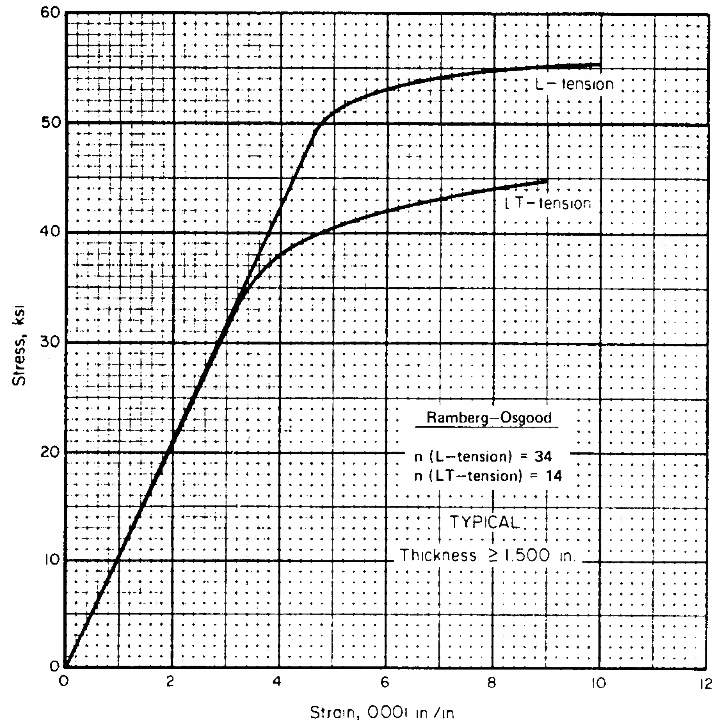

FIGURE 3.2.3.1.6(p). *Typical tensile stress-strain curves for 2024-T42 aluminum alloy extrusion at room temperature.*

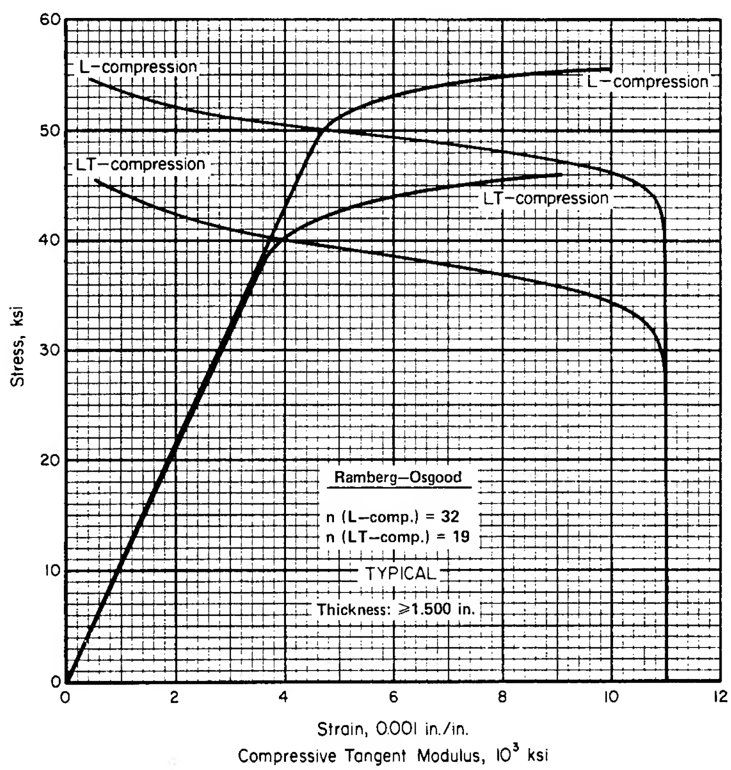

FIGURE 3.2.3.1.6(q). *Typical compressive stress-strain and compressive tangent-modulus curves for 2024-T42 aluminum alloy extrusion at room temperature.*

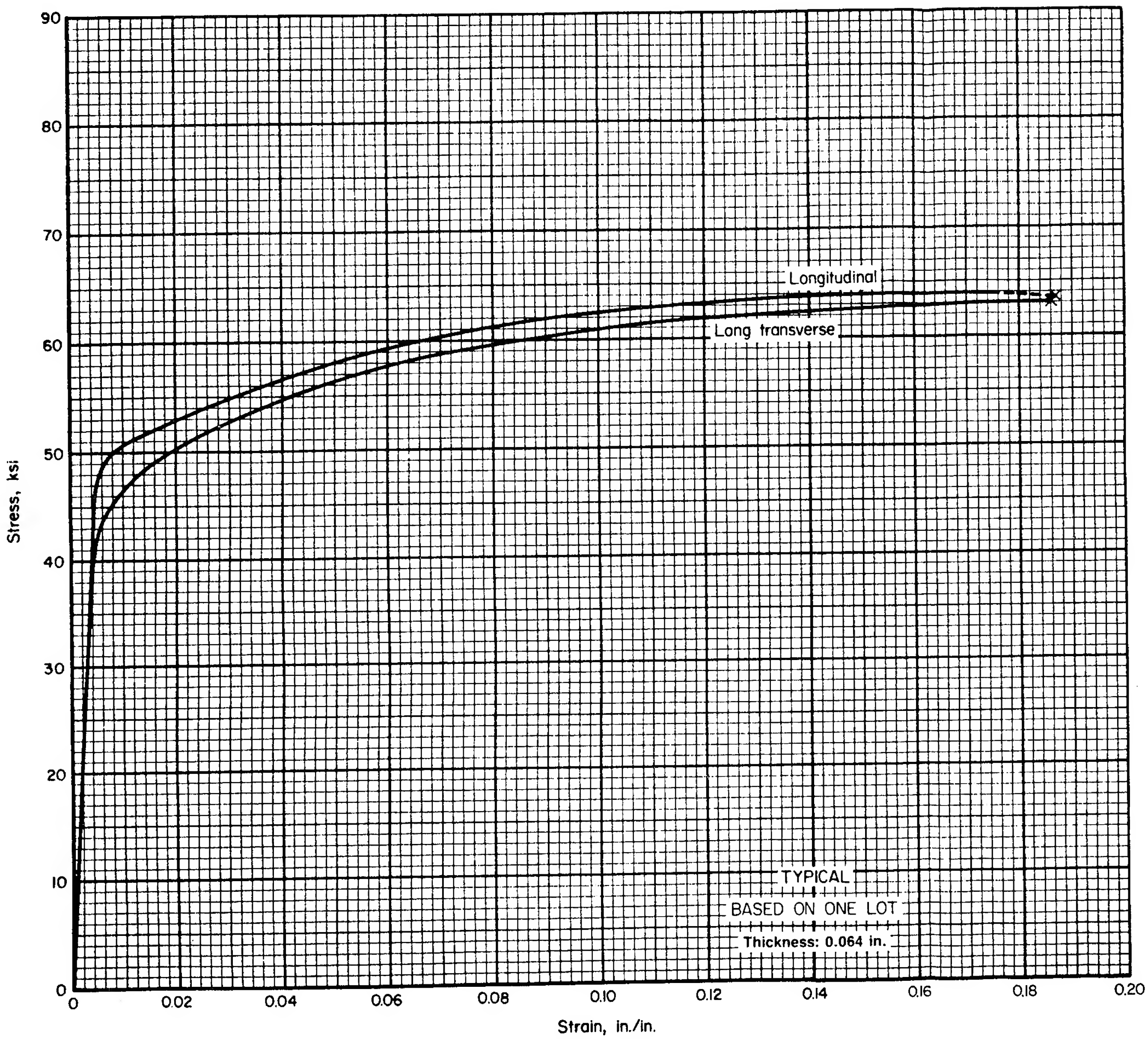

FIGURE 3.2.3.1.6(r). *Typical tensile stress-strain curves (full-range) for clad 2024-T3 aluminum alloy sheet at room temperature.*

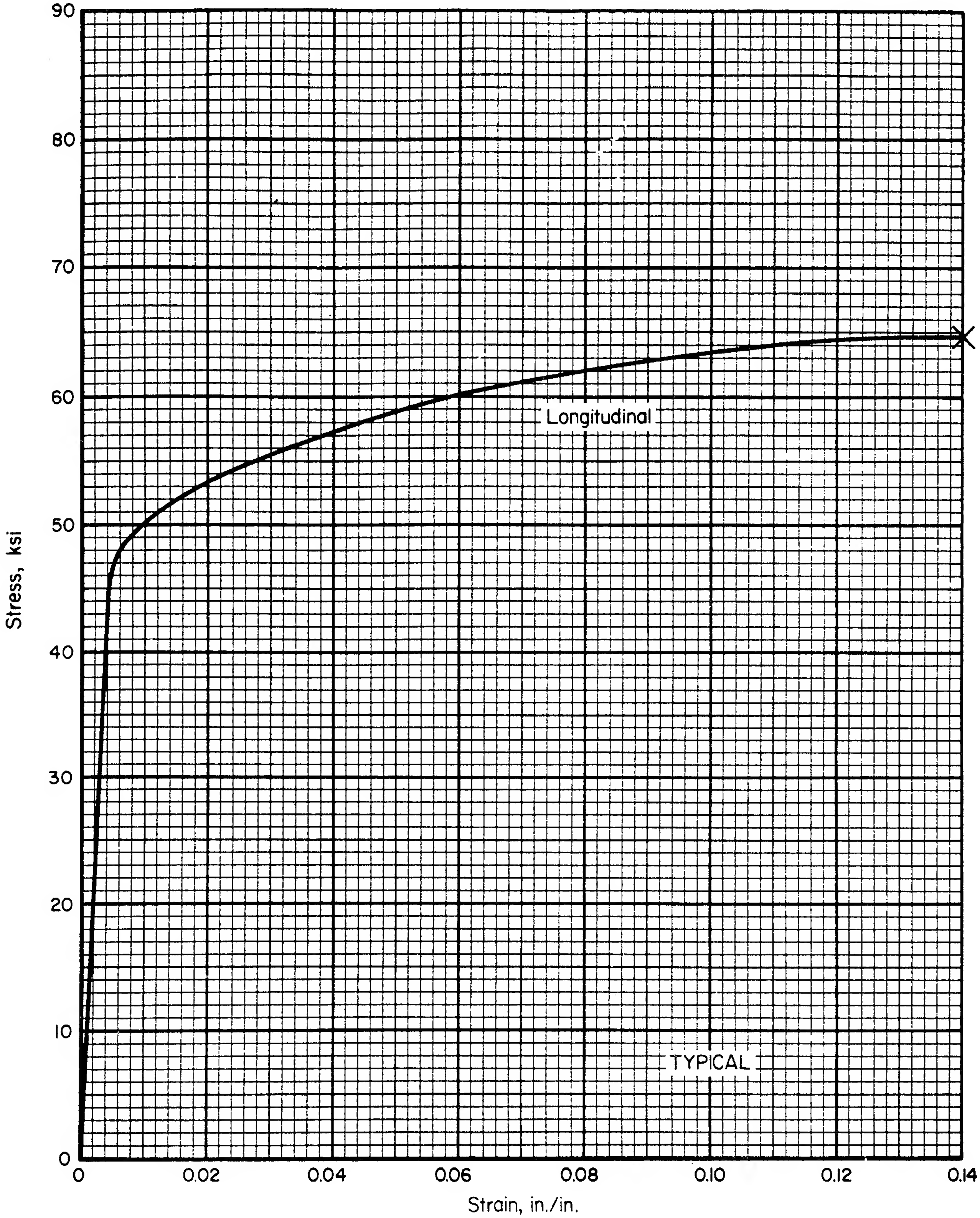

FIGURE 3.2.3.1.6(s). *Typical tensile stress-strain curve (full range) for 2024-T351 aluminum alloy rolled rod at room temperature.*

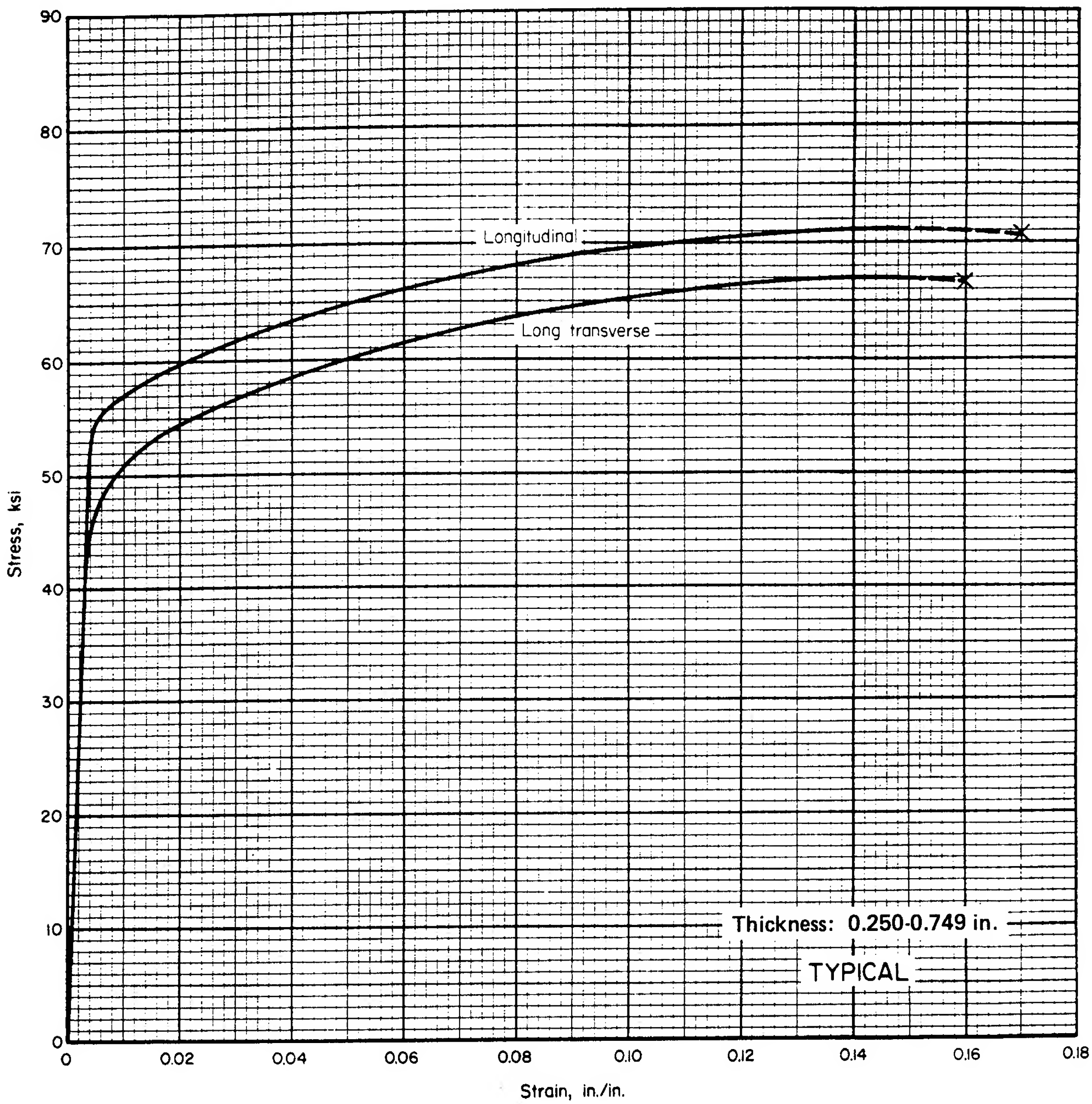

FIGURE 3.2.3.1.6(t). *Typical tensile stress-strain curve (full range) for 2024-T351X aluminum alloy extrusion at room temperature.*

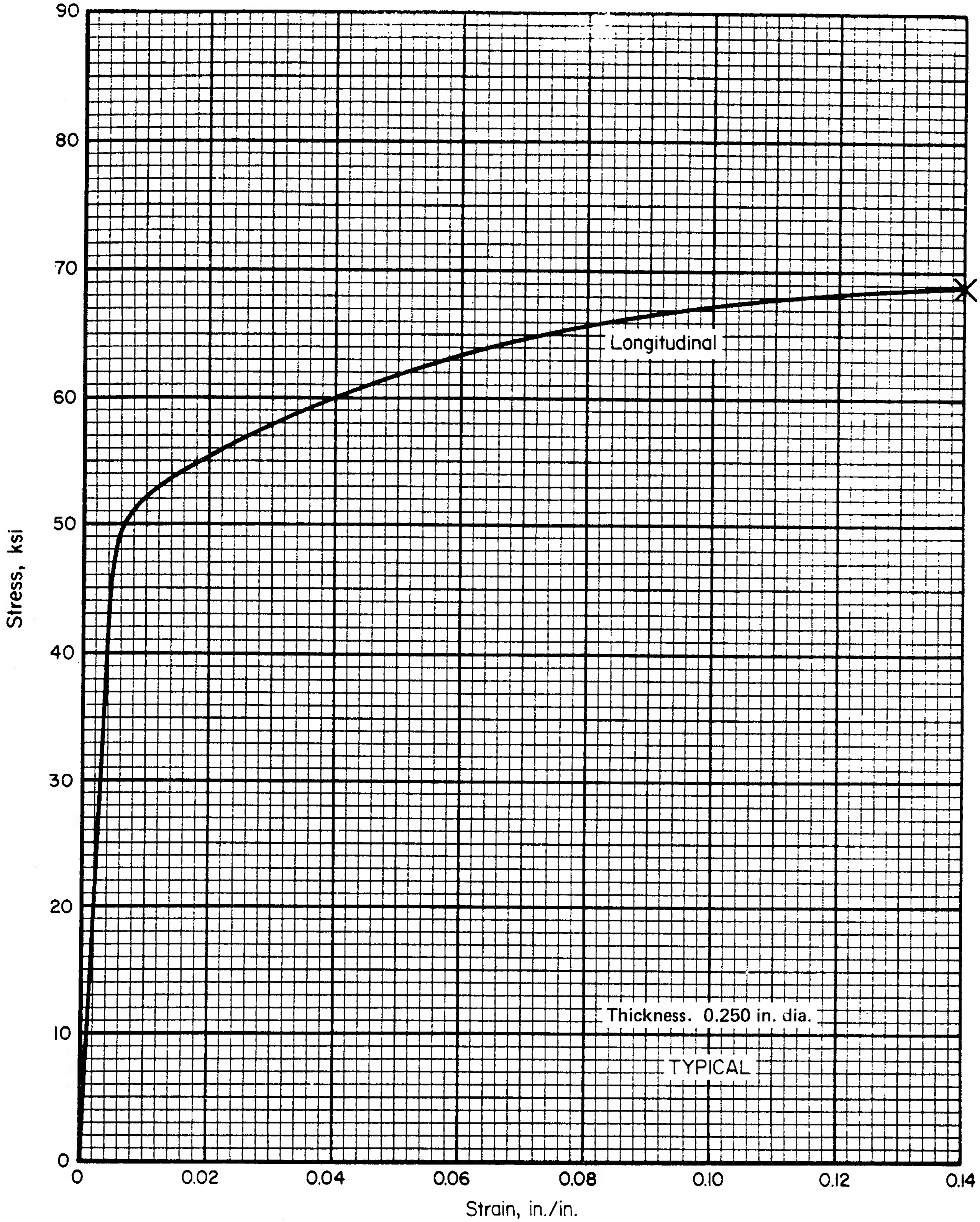

FIGURE 3.2.3.1.6(u). *Typical stress-strain curve (full range) for 2024-T3 aluminum alloy extrusion at room temperature.*

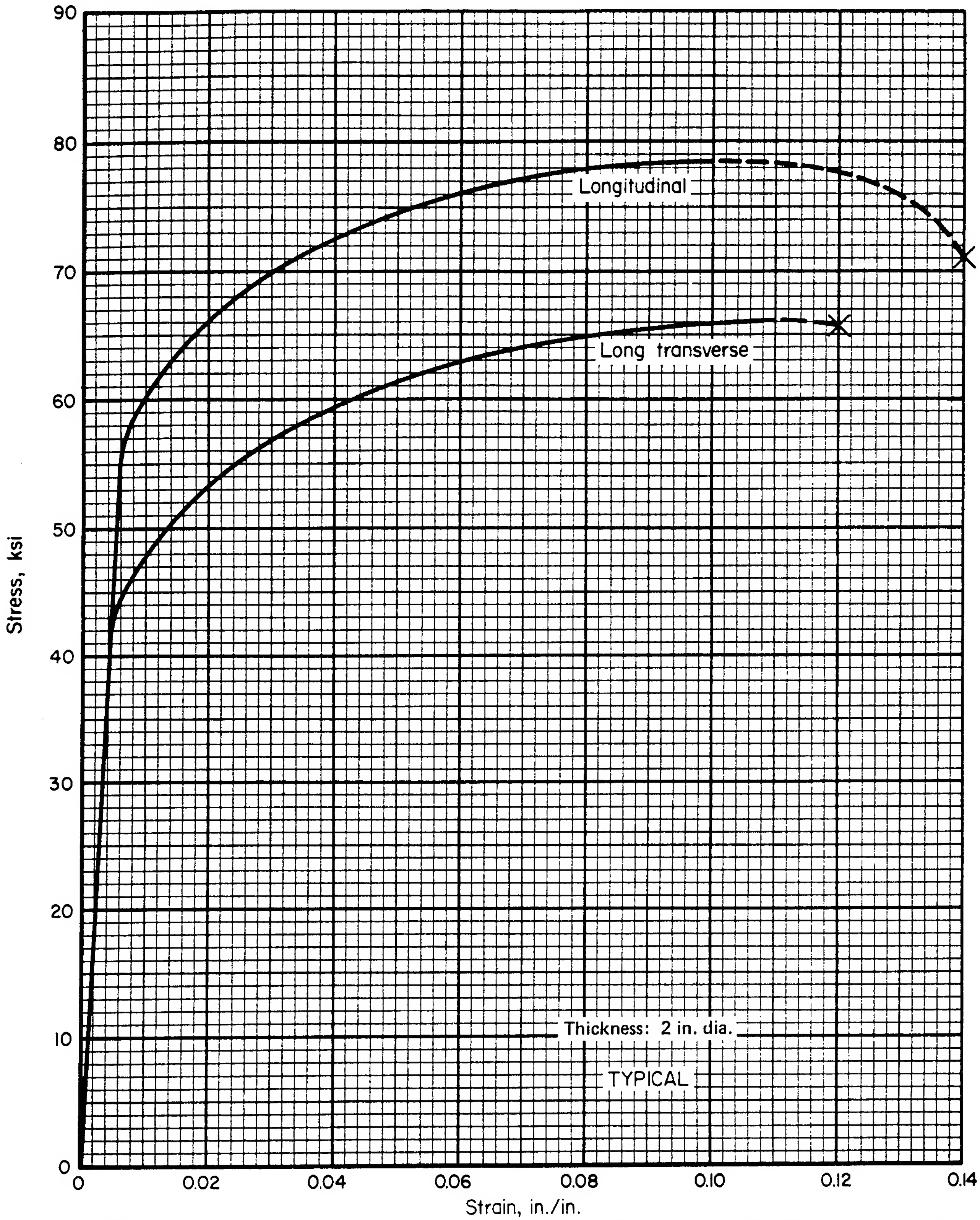

FIGURE 3.2.3.1.6(v). *Typical tensile stress-strain curves (full range) for 2024-T3 aluminum alloy extrusion at room temperature.*

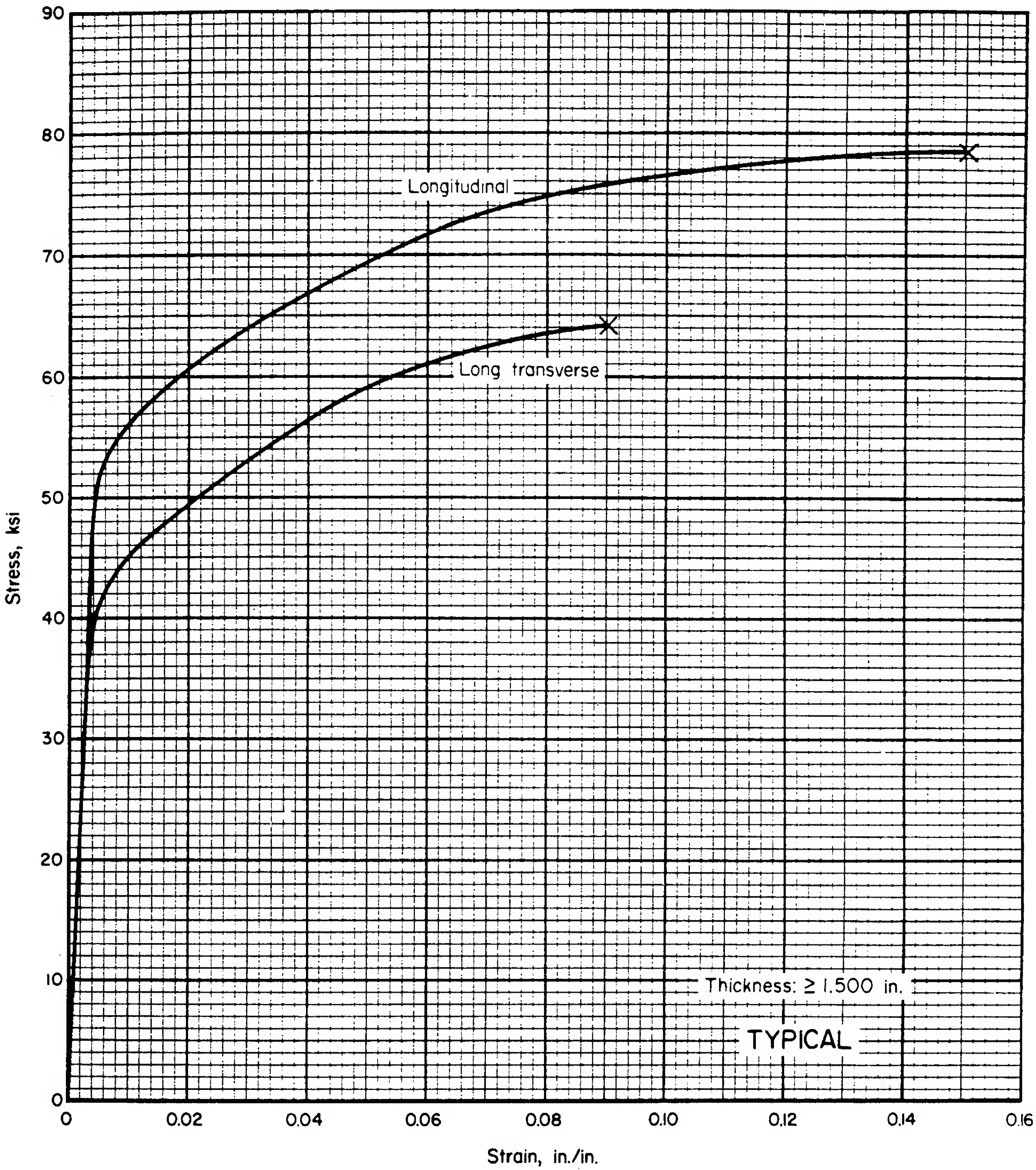

FIGURE 3.2.3.1.6(w). *Typical tensile stress-strain curves (full range) for 2024-T42 aluminum alloy extrusion at room temperature.*

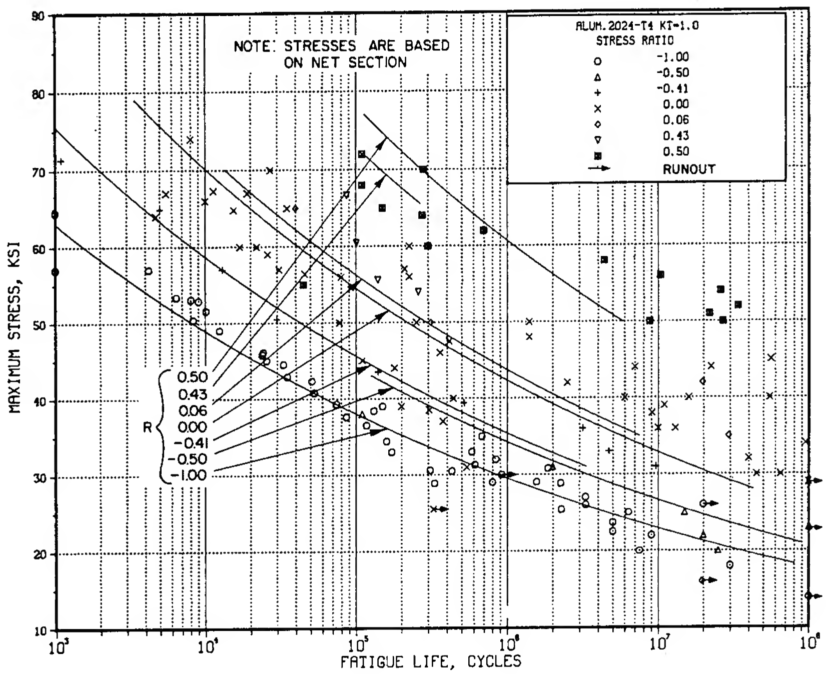

FIGURE 3.2.3.1.8(a). *Best-fit S/N curves for unnotched 2024-T4 aluminum alloy, various wrought products, longitudinal direction.*

Correlative Information for Figure 3.2.3.1.8(a)

Product Form: Rolled bar, 3/4 to 1/8 inch diameter
Drawn rod, 3/4-inch diameter
Extruded rod, 1-1/4-inch diameter
Extruded bar, 1-1/4 x 4-inch

Properties:	TUS, ksi	TYS, ksi	Temp., F
	69	45	RT (rolled)
	71	44	RT (drawn)
	85	65	RT (extruded)

Specimen Details: Unnotched
0.160 to 0.400-inch diameter

Surface Condition: Longitudinally Polished

References: 3.2.1.1.8(a) through (c) and 3.2.3.1.8(i)

Test Parameters:

Loading – Axial
Frequency – 1800 to 3600 cpm
Temperature – RT
Environment – Air

No. of Heats/Lots: Not specified

Equivalent Stress Equation:

Log N_f = 20.83–9.09 log (S_{eq})
$S_{eq} = S_{max} (1-R)^{0.52}$
Standard Error of Estimate = 0.566
Standard Deviation in Life = 1.324
R^2 = 82%

Sample Size = 134

[Caution: The equivalent stress model may provide unrealistic life predictions for stress ratios beyond those represented above]

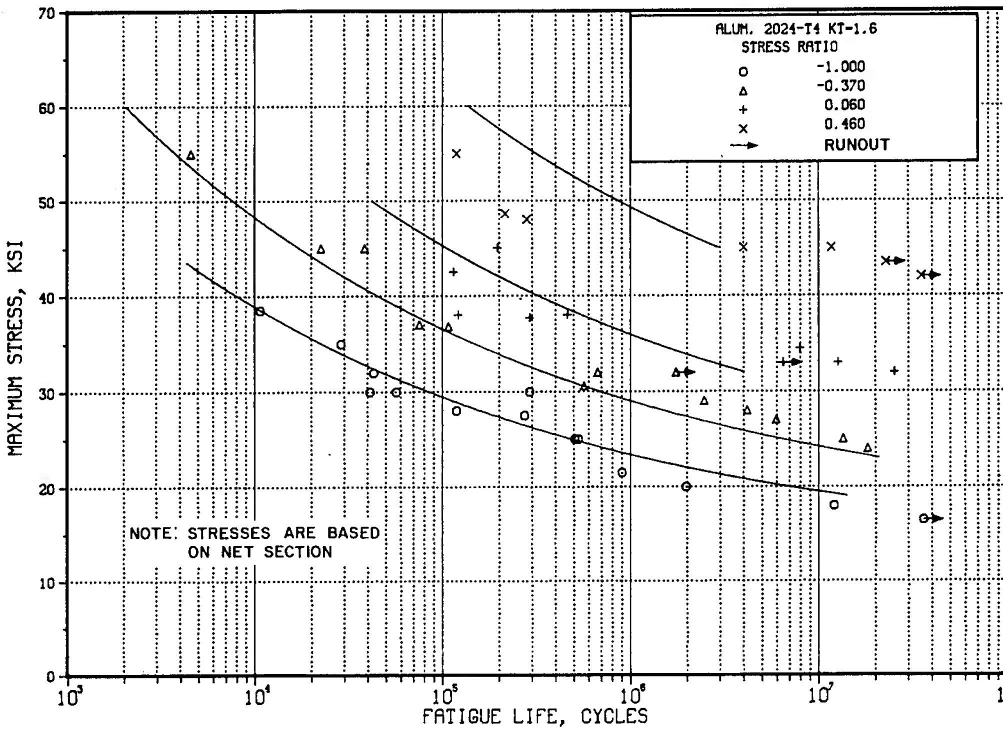

FIGURE 3.2.3.1.8(b). *Best-fit S/N curves for notched, K_t = 1.6, 2024-T4 aluminum alloy bar, longitudinal direction.*

Correlative Information for Figure 3.2.3.1.8(b)

Product Form: Rolled bar, 1-1/8-inch diameter

Properties:	TUS, ksi	TYS, ksi	Temp., F
	73	49	RT

Specimen Details: Semicircular V-Groove, K_t = 1.6

0.450-inch gross diameter
0.400-inch net diameter
0.100-inch root radius, r
60° flank angle, ω

Surface Condition: As machined

Reference: 3.2.1.1.8(b)

Test Parameters:

Loading - Axial
Frequency - 1800 to 3600 cpm
Temperature - RT
Environment - Air

No. of Heats/Lots: Not specified

Equivalent Stress Equation:

$\log N_f = 12.25 - 5.16 \log (S_{eq} - 18.7)$
$S_{eq} = S_{max} (1-R)^{0.57}$
Standard Error of Estimate = 0.414
Standard Deviation in Life = 0.989
R^2 = 82%

Sample Size = 38

[Caution: The equivalent stress model may provide unrealistic life predictions for stress ratios beyond those represented above]

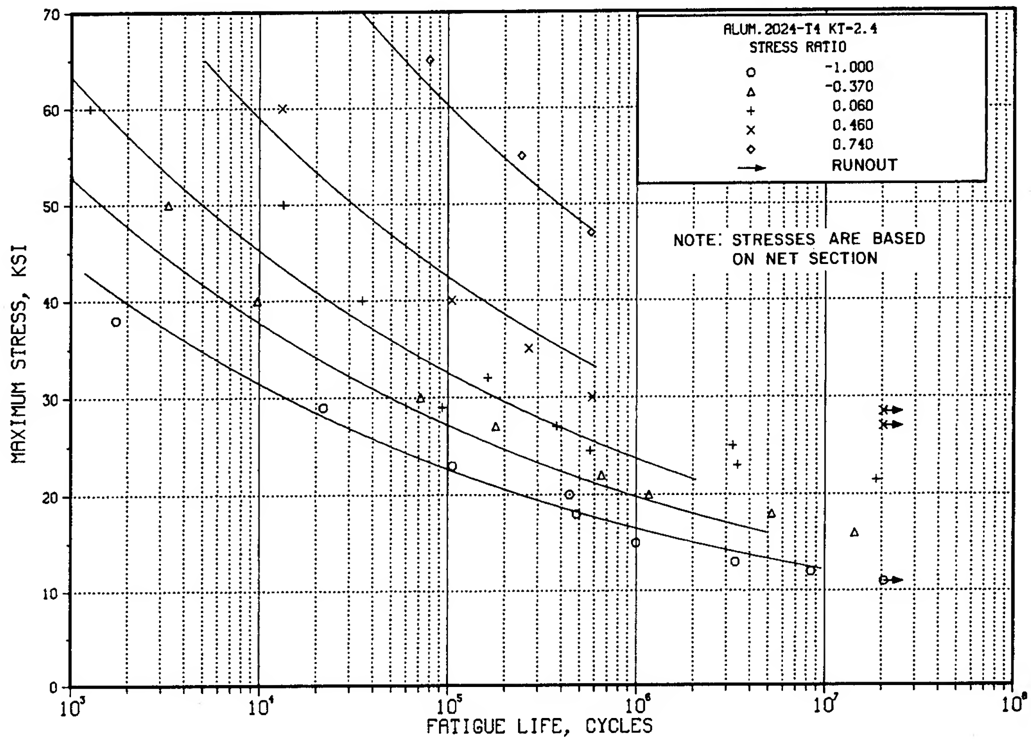

FIGURE 3.2.3.1.8(c). *Best-fit S/N curves for notched, K_t = 2.4, 2024-T4 aluminum alloy bar, longitudinal direction.*

Correlative Information for Figure 3.2.3.1.8(c)

Product Form: Rolled bar, 1-1/8 inch diameter

Properties:

TUS, ksi	TYS, ksi	Temp., F
73	49	RT

Specimen Details: Circumferential V-Groove, K_t = 2.4

0.500-inch gross diameter
0.400-inch net diameter
0.032-inch root radius, r
60° flank angle, ω

Surface Condition: As machined

Reference: 3.2.1.1.8(b)

Test Parameters:

Loading – Axial
Frequency – 1800 to 3600 cpm
Temperature – RT
Environment – Air

No. of Heats/Lots: Not specified

Equivalent Stress Equation:

Log N_f = 14.33–6.35 log (S_{eq}–3.2)
$S_{eq} = S_{max} (1-R)^{0.48}$
Standard Error of Estimate = 0.310
Standard Deviation in Life = 1.084
R^2 = 92%

Sample Size = 33

[Caution: The equivalent stress model may provide unrealistic life predictions for stress ratios beyond those represented above]

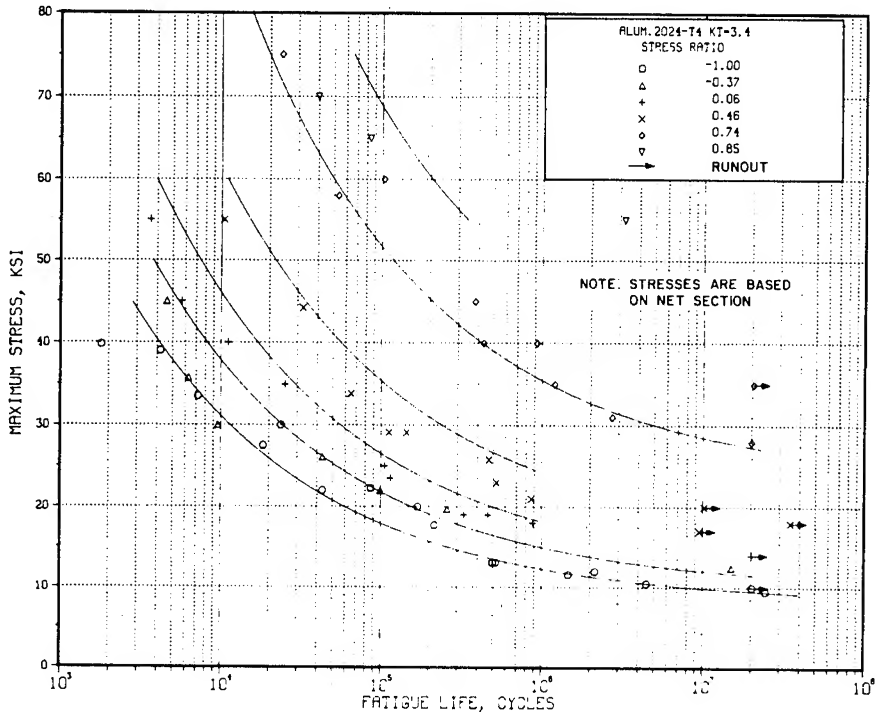

FIGURE 3.2.3.1.8(d). *Best-fit S/N curves for notched, K_t = 3.4, 2024-T4 aluminum alloy, various wrought products, longitudinal direction.*

Correlative Information for Figure 3.2.3.1.8(d)

Product Form: Rolled bar, 1-1/8-inch diameter
Extruded bar, 1-1/4-inch diameter

Properties:	TUS, ksi	TYS, ksi	Temp., F
	74.2	—	RT (rolled)
	84.1	—	RT (extruded)

Specimen Details: Circumferential V-Groove, K_t = 3.4

0.450-inch gross diameter
0.400-inch net diameter
0.010-inch root radius, r
60° flank angle, ω

Surface Condition: As machined

References: 3.2.1.1.8(b) and (c)

Test Parameters:

Loading - Axial
Frequency - 1800 to 3600 cpm
Temperature - RT
Environment - Air

No. of Heats/Lots: Not specified

Equivalent Stress Equation:

$\log N_f = 8.14 - 2.76 \log (S_{eq} - 11.6)$
$S_{eq} = S_{max} (1-R)^{0.52}$
Standard Error of Estimate = 0.292
Standard Deviation in Life = 1.011
R^2 = 92%

Sample Size = 51

[Caution: The equivalent stress model may provide unrealistic life predictions for stress ratios beyond those represented above]

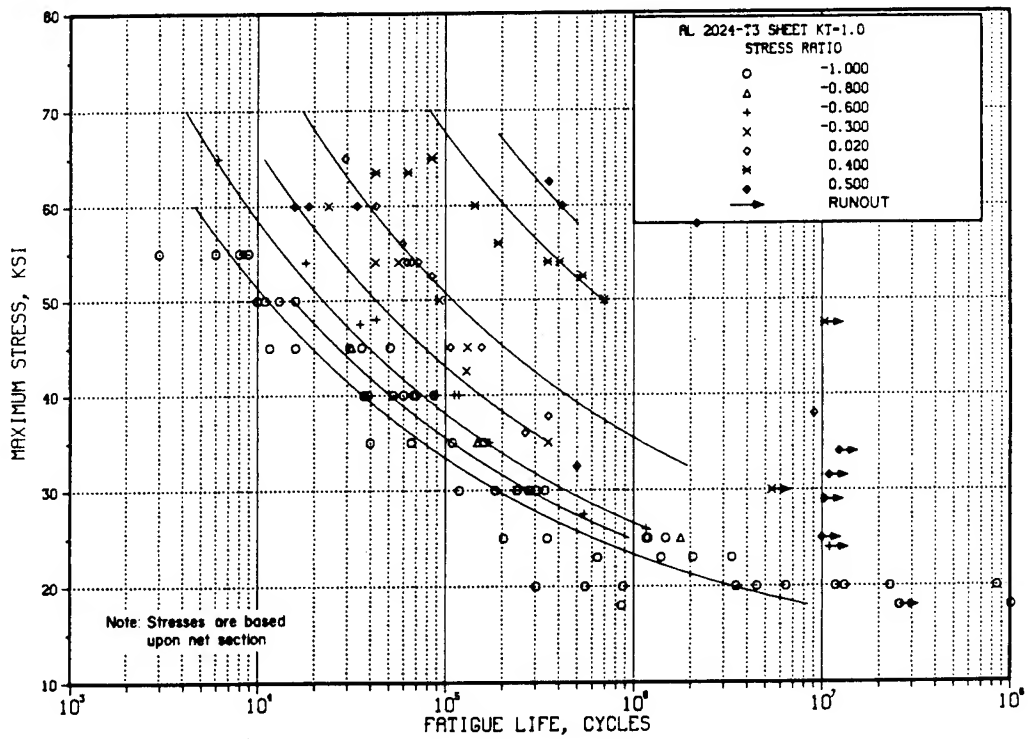

FIGURE 3.2.3.1.8(e). *Best-fit S/N curves for unnotched 2024-T3 aluminum alloy sheet, longitudinal direction.*

Correlative Information for Figure 3.2.3.1.8(e)

Product Form: Bare sheet, 0.090 inch

Properties:	TUS, ksi	TYS, ksi	Temp., F
	72, 73	52, 54	RT

Specimen Details: Unnotched
0.8 to 1.0 inch width

Surface Condition: Electropolished

Reference: 3.2.3.1.8(a) and (f)

Test Parameters:

Loading – Axial
Frequency – 1100 to 1800 cpm

No. of Heats/Lots: Not specified

Equivalent Stress Equation:

Log N_f = 11.1–3.97 log (S_{eq}–15.8)
$S_{eq} = S_{max}\,(1\text{-}R)^{0.56}$
Standard Error of Estimate = 0.38
Standard Deviation in Life = 0.90
R^2 = 82%

Sample Size = 107

[Caution: The equivalent stress model may provide unrealistic life predictions for stress ratios beyond those represented above]

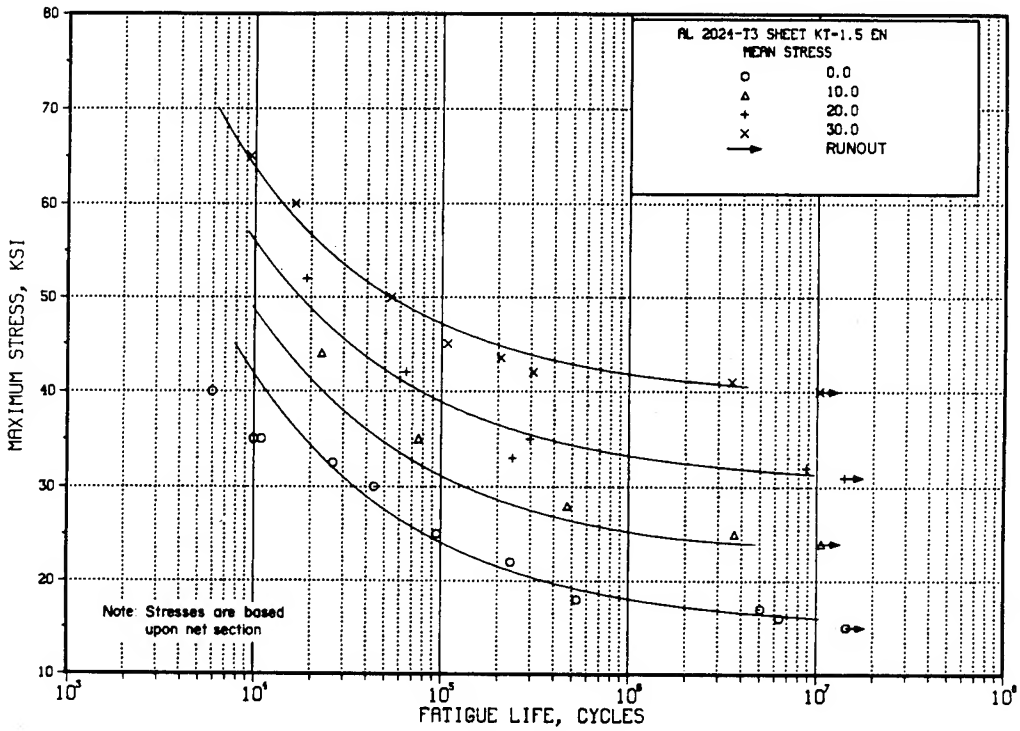

FIGURE 3.2.3.1.8(f). *Best-fit S/N curves for notched, K_t = 1.5, 2024-T3 aluminum alloy sheet, longitudinal direction.*

Correlative Information for Figure 3.2.3.1.8(f)

Product Form: Bare sheet, 0.090 inch

Properties:	TUS, ksi	TYS, ksi	Temp., F
	73	54	RT (unnotched)
	76	—	RT (notched K_t = 1.5)

Specimen Details: Edge notched, K_t = 1.5
3.00 inches gross width
1.500 inches net width
0.760 inch notch radius
0° flank angle

Surface Condition: Electropolished

Reference: 3.2.3.1.8(d)

Test Parameters:

Loading – Axial
Frequency – 1100 to 1500 cpm
Temperature – RT
Environment – Air

No. of Heats/Lots: Not specified

Equivalent Stress Equation:

Log N_f = 7.5–2.13 log (S_{eq}–23.7)
$S_{eq} = S_{max}$ $(1\text{-}R)^{0.66}$
Standard Error of Estimate = 0.30
Standard Deviation in Life = 0.95
R^2 = 90%

Sample Size = 26

[Caution: The equivalent stress model may provide unrealistic life predictions for stress ratios beyond those represented above]

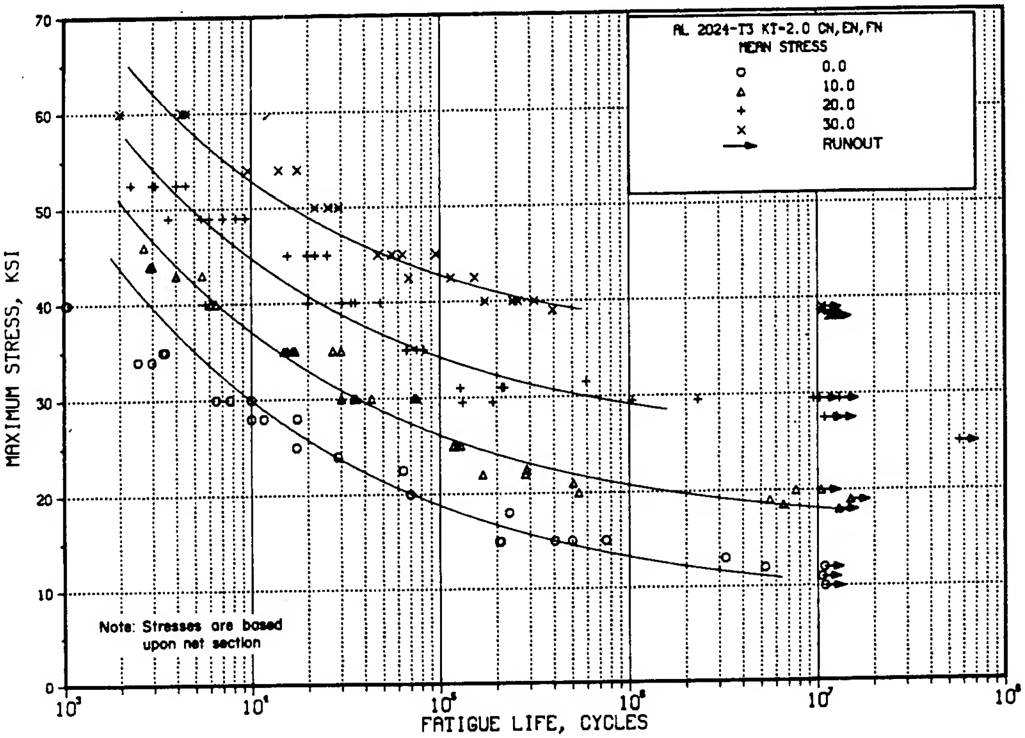

FIGURE 3.2.3.1.8(g). *Best-fit S/N curves for notched, K_t = 2.0, 2024-T3 aluminum alloy sheet, longitudinal direction.*

Correlative Information for Figure 3.2.3.1.8(g)

Product Form: Bare sheet, 0.090 inch

Properties:	TUS, ksi	TYS, ksi	Temp., F
	73	54	RT (unnotched)
	73	—	RT (notched K_t = 2.0)

Specimen Details: Notched, K_t = 2.0

Notch Type	Gross Width	Net Width	Notch Radius
Center	4.50	1.50	1.50
Edge	2.25	1.50	0.3175
Fillet	2.25	1.50	0.1736

Surface Condition: Electropolished, machined and burrs removed with fine crocus cloth

References: 3.2.3.1.8(b) and (f)

Test Parameters:

Loading – Axial
Frequency – 1100 to 1800 cpm
Temperature – RT
Environment – Air

No. of Heats/Lots: Not specified

Equivalent Stress Equation:

$\log N_f = 9.2 - 3.33 \log (S_{eq} - 12.3)$
$S_{eq} = S_{max} (1-R)^{0.68}$
Standard Error of Estimate = 0.27
Standard Deviation in Life = 0.89
R^2 = 91%

Sample Size = 113

[Caution: The equivalent stress model may provide unrealistic life predictions for stress ratios beyond those represented above]

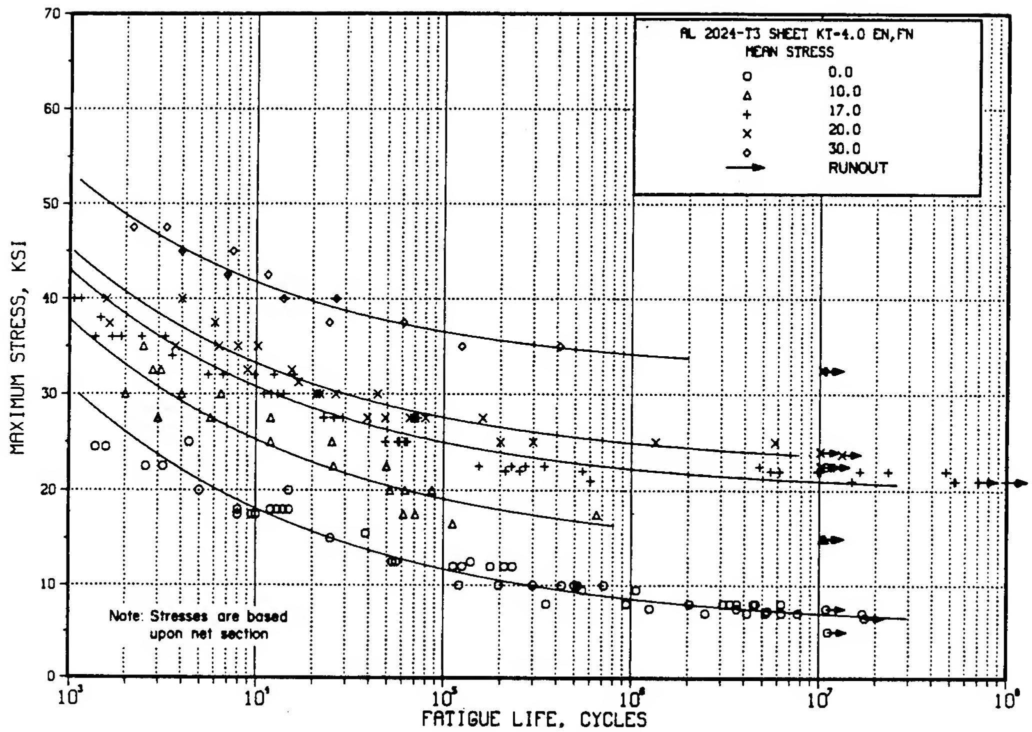

FIGURE 3.2.3.1.8(h). *Best-fit S/N curves for notched, K_t = 4.0 of 2024-T3 aluminum alloy sheet, longitudinal direction.*

Correlative Information for Figure 3.2.3.1.8(h)

Product Form: Bare sheet, 0.090 inch

Properties:	TUS, ksi	TYS, ksi	Temp., F
	73	54	RT (unnotched)
	67	—	RT (notched, K_t = 4.0)

Specimen Details: Notched, K_t = 2.0

Notch Type	Gross Width	Net Width	Notch Radius
Edge	2.25	1.50	0.057
Edge	4.10	1.50	0.070
Fillet	2.25	1.50	0.0195

Surface Condition: Electropolished, machined, and burrs removed with fine crocus cloth

Reference: 3.2.3.1.8(b), (e), (f), (g), and (h)

Test Parameters:

Loading - Axial
Frequency - 1100 to 1800 cpm
Temperature - RT
Environment - Air

No. of Heats/Lots: Not specified

Equivalent Stress Equation:

Log N_f = 8.3–3.30 log (S_{eq} – 8.5)
$S_{eq} = S_{max} (1\text{-}R)^{0.66}$
Standard Error of Estimate = 0.39
Standard Deviation in Life = 1.24
R^2 = 90%

Sample Size = 126

[Caution: The equivalent stress model may provide unrealistic life predictions for stress ratios beyond those represented above]

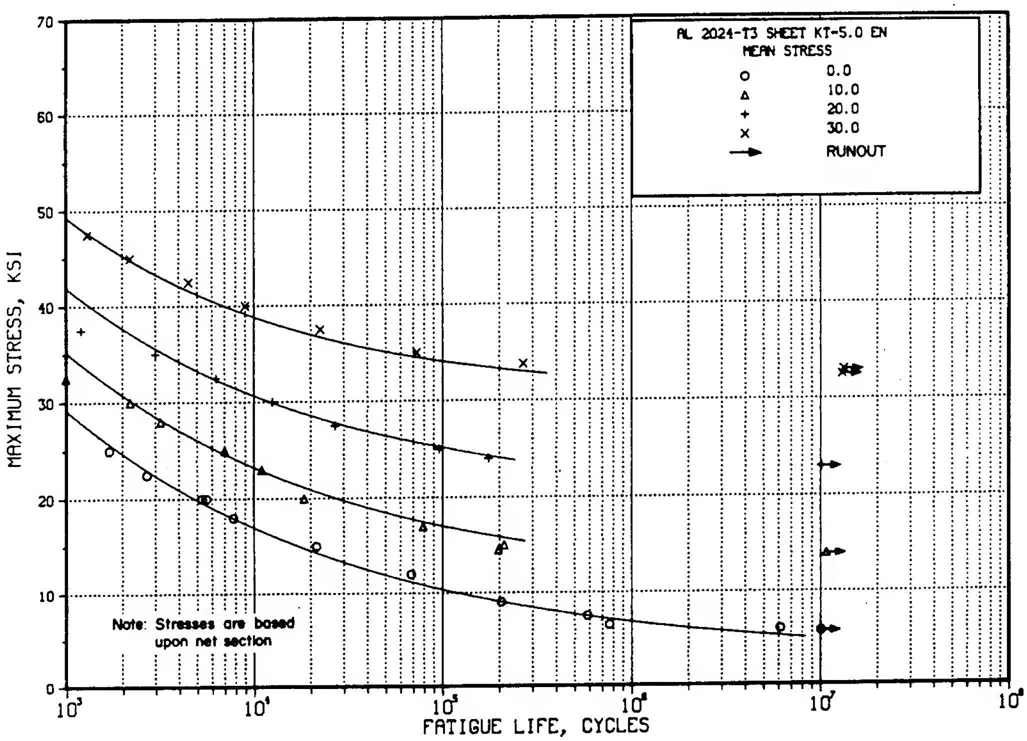

FIGURE 3.2.3.1.8(i). *Best-fit S/N curves for notched, K_t = 5.0, 2024-T3 aluminum alloy sheet, longitudinal direction.*

Correlative Information for Figure 3.2.3.1.8(i)

Product Form: Bare sheet, 0.090 inch

Properties:

TUS, ksi	TYS, ksi	Temp., F
73	54	RT (unnotched)
62	—	RT (notched K_t = 5.0)

Specimen Details: Edge notched, K_t = 5.0
2.25-inch gross width
1.500-inch net width
0.03125-inch notch radius
0° flank angle

Surface Condition: Electropolished

Reference: 3.2.3.1.8(c)

Test Parameters:

Loading - Axial
Frequency - 1100 to 1800 cpm
Temperature - RT
Environment - Air

No. of Heats/Lots: Not specified

Equivalent Stress Equation:

$\text{Log } N_f = 8.9 - 3.73 \log (S_{eq} - 3.9)$
$S_{eq} = S_{max} (1-R)^{0.56}$
Standard Error of Estimate = 0.39
Standard Deviation in Life = 1.24
R^2 = 90%

Sample Size = 35

[Caution: The equivalent stress model may provide unrealistic life predictions for stress ratios beyond those represented above]

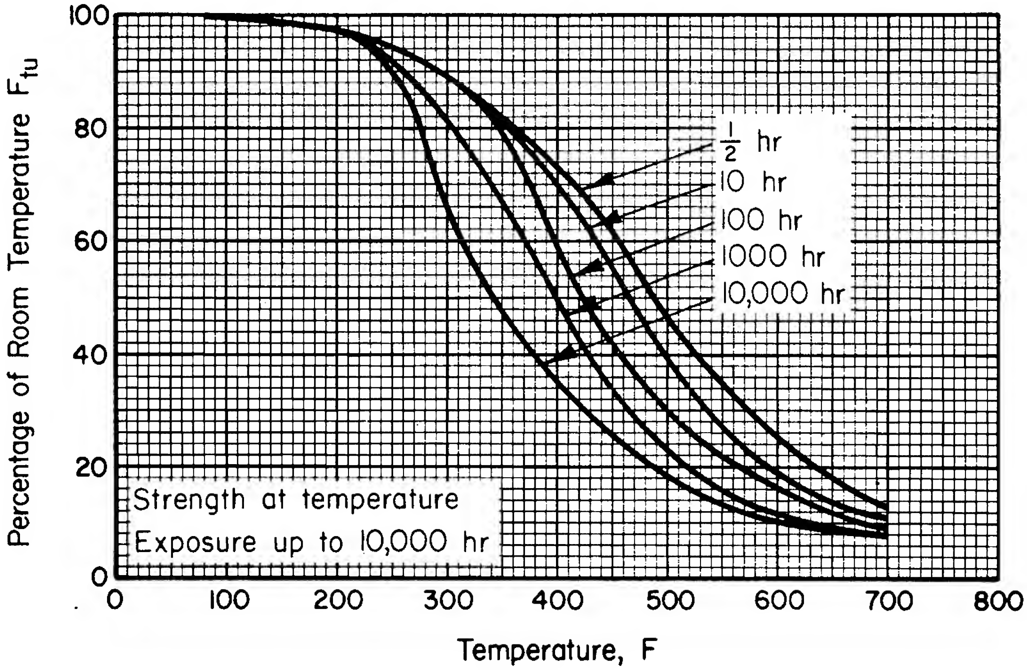

FIGURE 3.2.3.3.1(a). *Effect of temperature on the tensile ultimate strength (F_{tu}) of 2024-T62 aluminum alloy (all products.)*

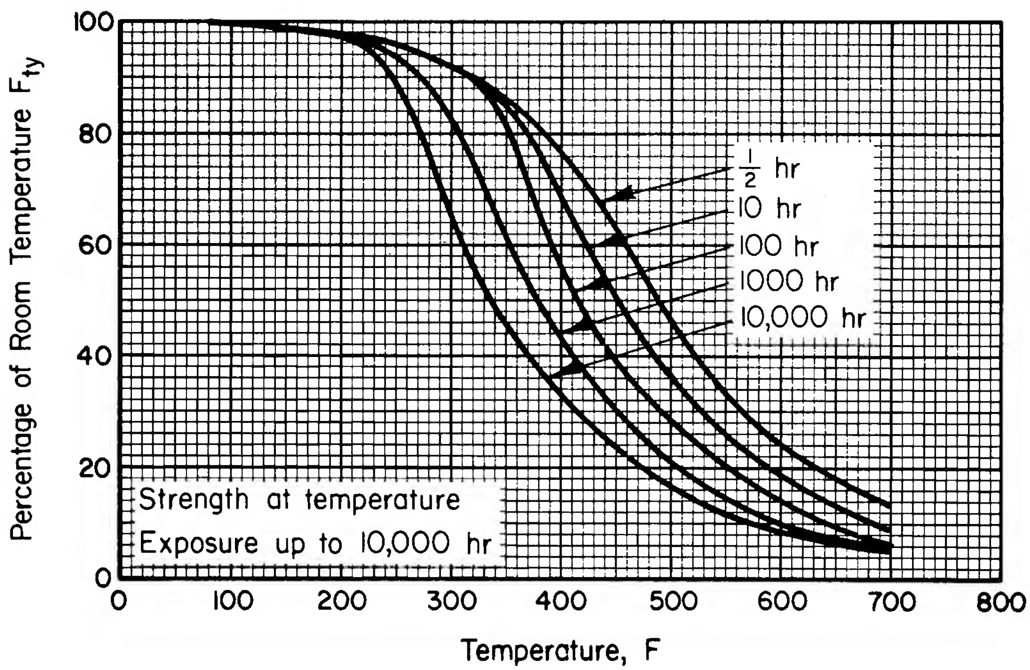

FIGURE 3.2.3.3.1(b). *Effect of temperature on the tensile yield strength (F_{ty}) of 2024-T62 aluminum alloy (all products).*

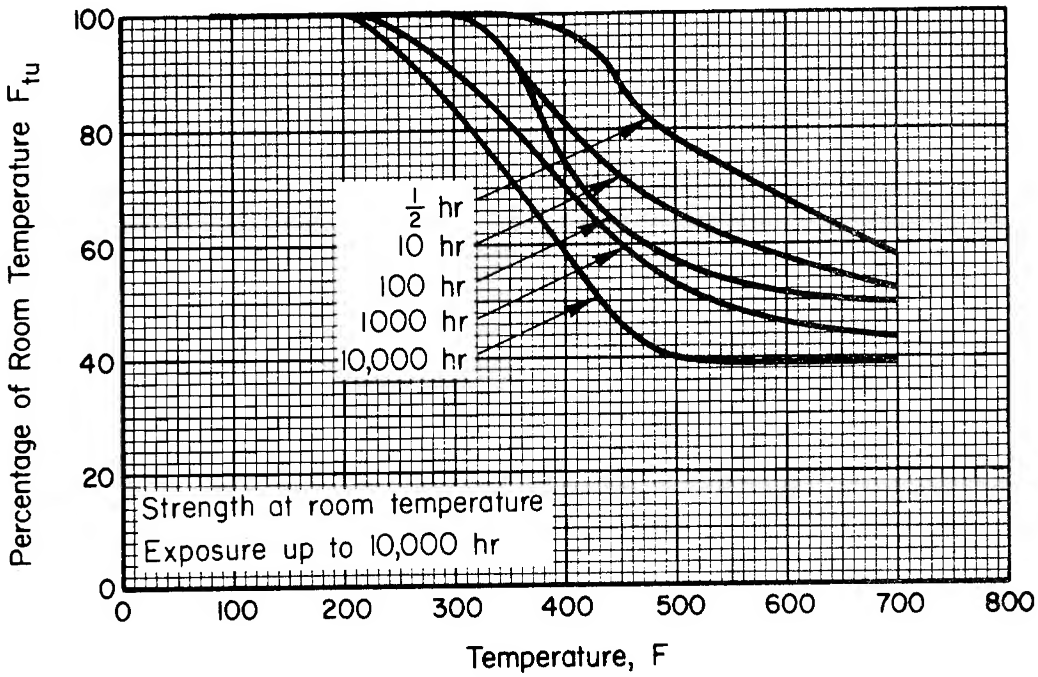

FIGURE 3.2.3.3.1(c). *Effect of exposure at elevated temperatures on the room-temperature tensile ultimate strength (F_{tu}) of 2024-T62 aluminum alloy (all products).*

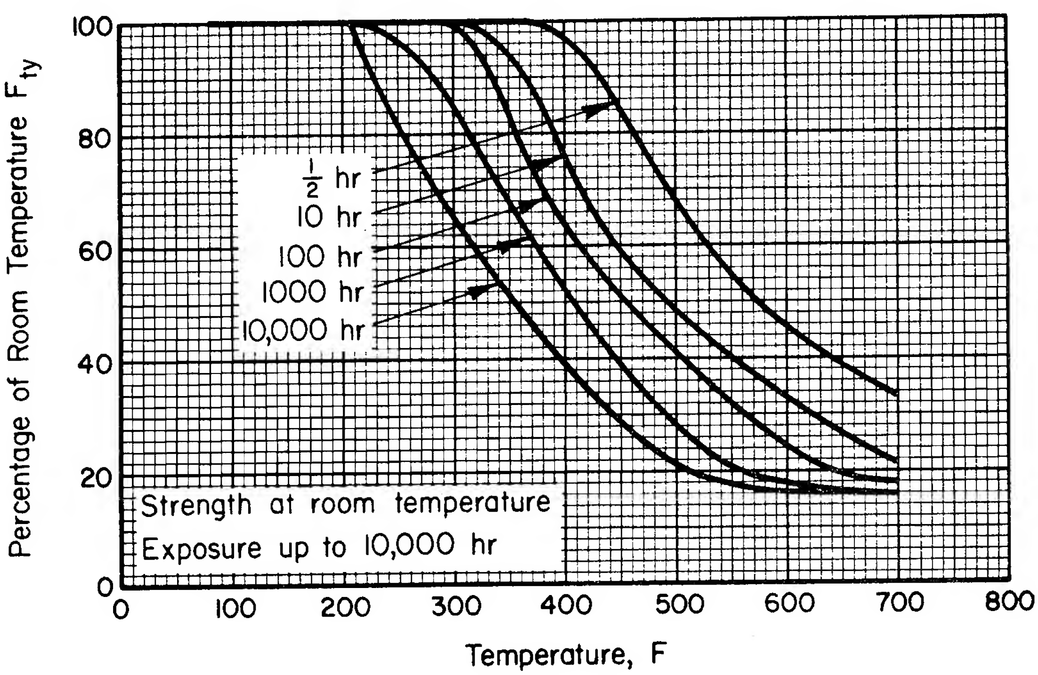

FIGURE 3.2.3.3.1(d). *Effect of exposure at elevated temperatures on the room-temperature tensile yield strength (F_{ty}) of 2024-T62 aluminum alloy (all products).*

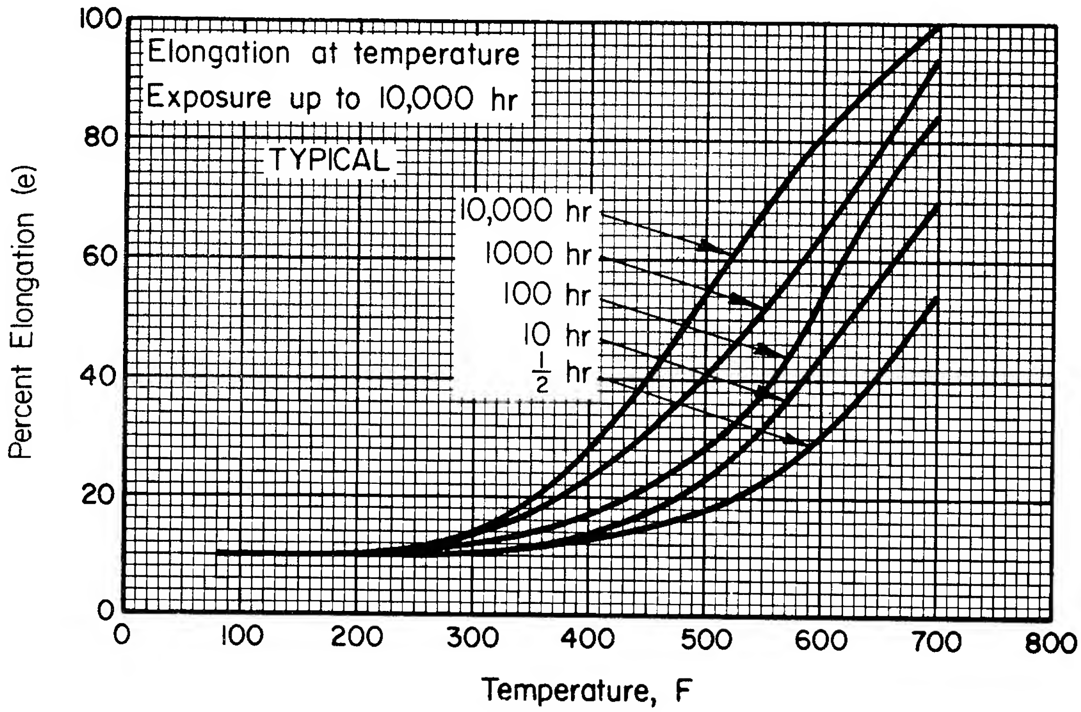

FIGURE 3.2.3.3.5(a). *Effect of temperature on the elongation of 2024-T62 aluminum alloy (all products).*

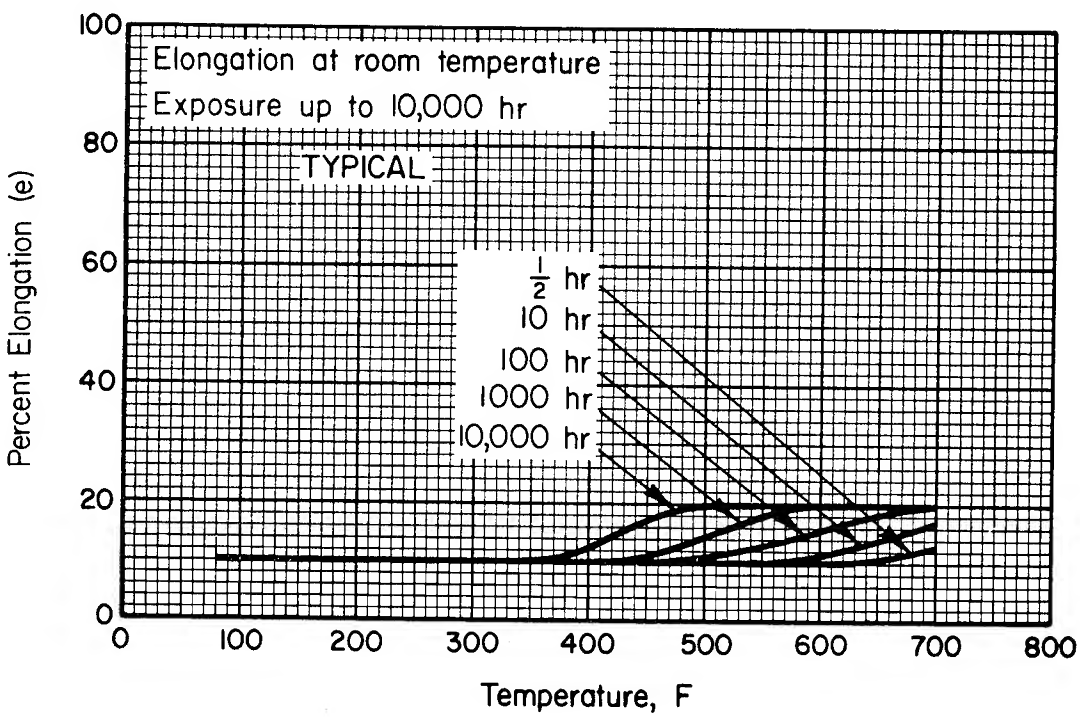

FIGURE 3.2.3.3.5(b). *Effect of exposure at elevated temperatures on the elongation of 2024-T62 aluminum alloy (all products).*

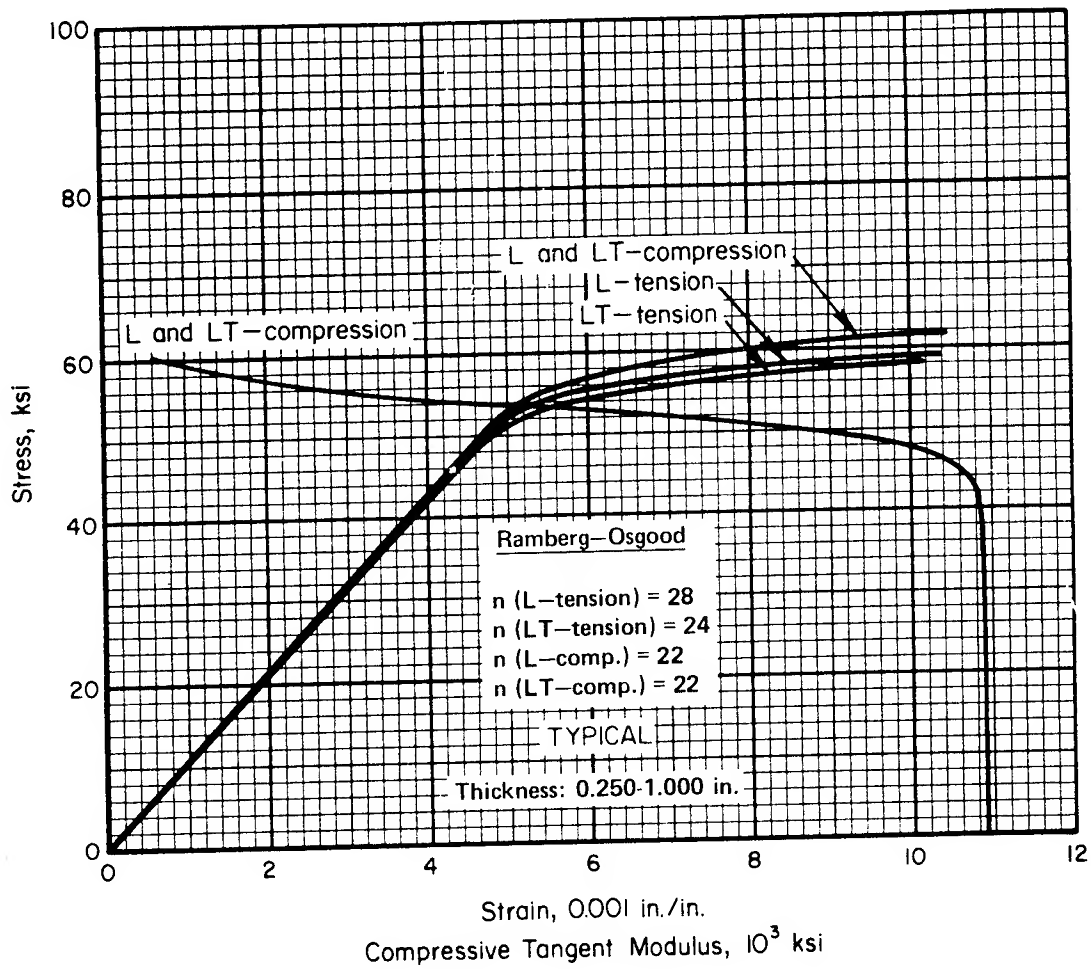

FIGURE 3.2.3.3.6. *Typical tensile and compressive stress-strain and compressive tangent-modulus curves for 2024-T62 aluminum alloy plate at room temperature.*

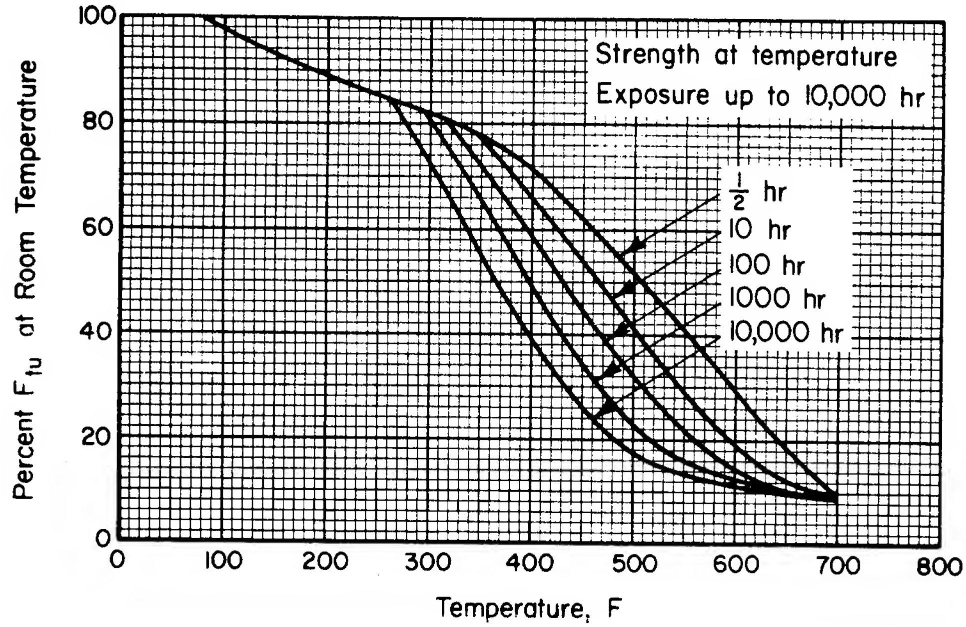

FIGURE 3.2.3.4.1(a). *Effect of temperature on the ultimate tensile strength (F_{tu}) of 2024-T81, T851, T8510 and T8511 aluminum alloy (all products).*

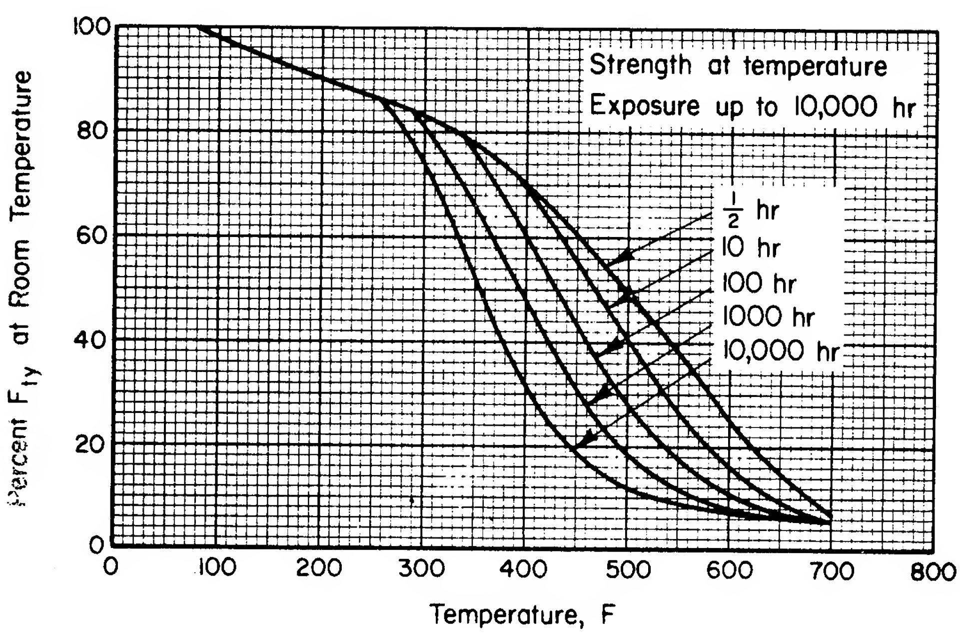

FIGURE 3.2.3.4.1(b). *Effect of temperature on the tensile yield strength (F_{ty}) of 2024-T81, T851, T8510 and T8511 aluminum alloy (all products).*

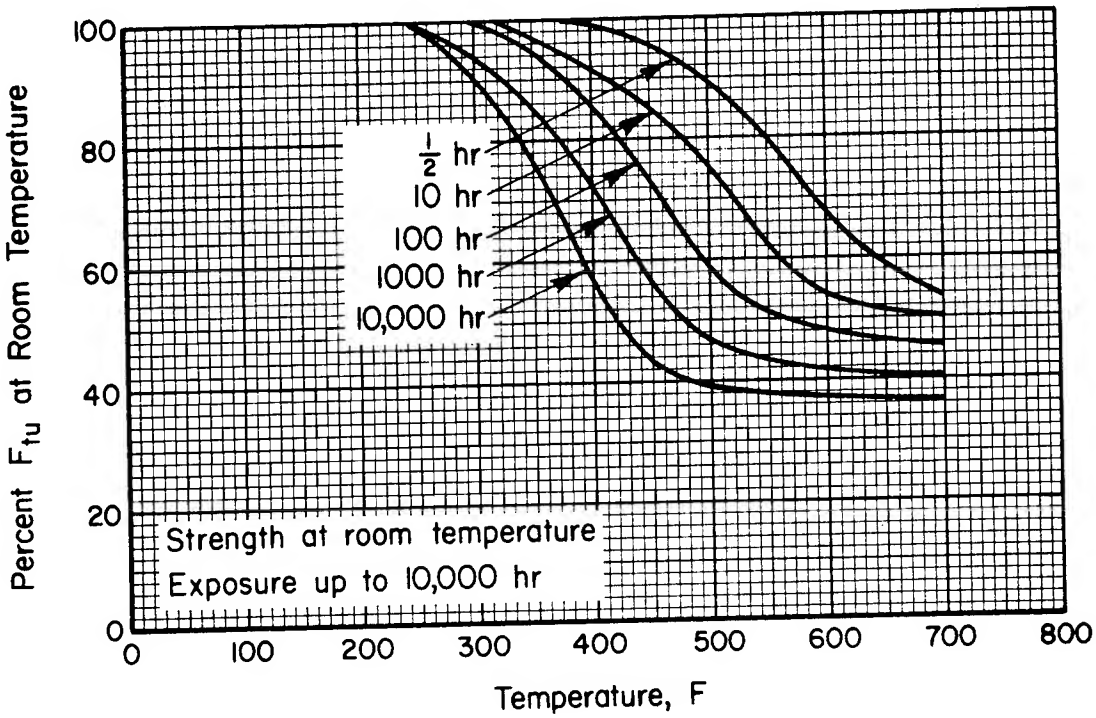

FIGURE 3.2.3.4.1(c). *Effect of exposure at elevated temperatures on room-temperature ultimate tensile strength (F_{tu}) of 2024-T81 aluminum alloy sheet.*

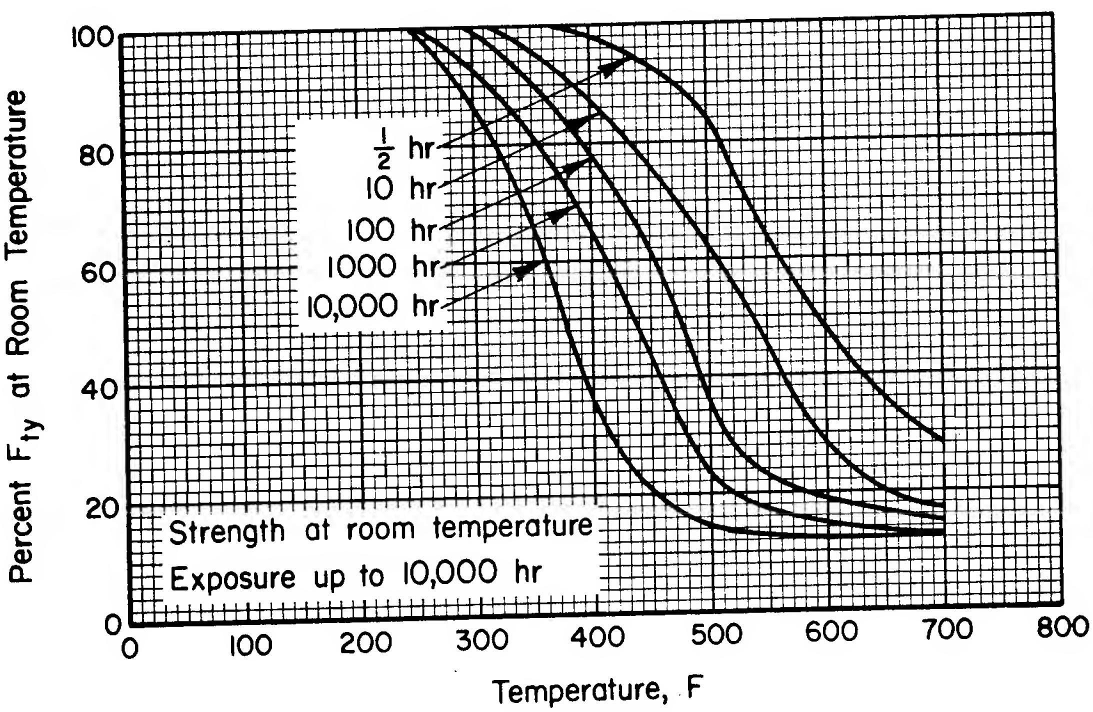

FIGURE 3.2.3.4.1(d). *Effect of exposure at elevated temperatures on the room temperature tensile yield strength (F_{ty}) of 2024-T81 aluminum alloy sheet.*

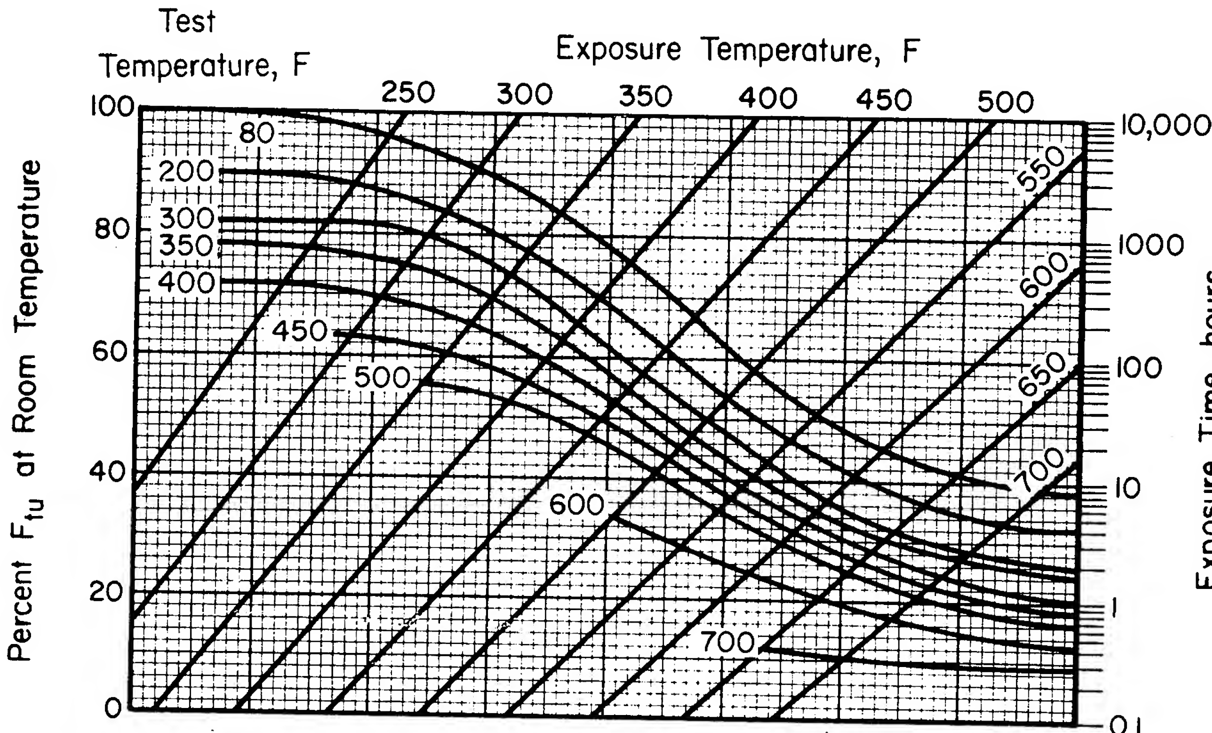

FIGURE 3.2.3.4.1(e). *Effect of temperature on the ultimate tensile strength (F_{tu}) of 2024-T81 aluminum alloy clad sheet. Note: Instructions for use of these curves are presented in Section 3.7.4.1.*

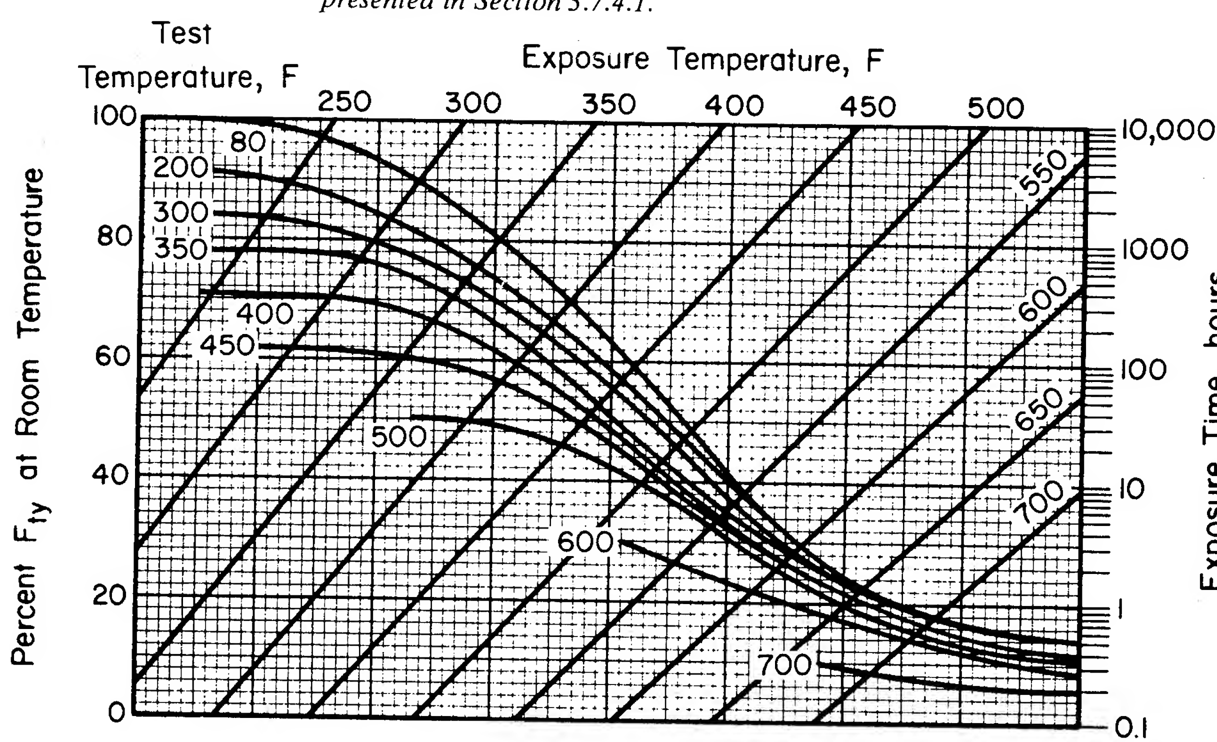

FIGURE 3.2.3.4.1(f). *Effect of temperature on the tensile yield strength (F_{ty}) of 2024-T81 aluminum alloy clad sheet. Note: Instructions for use of these curves are presented in Section 3.7.4.1.*

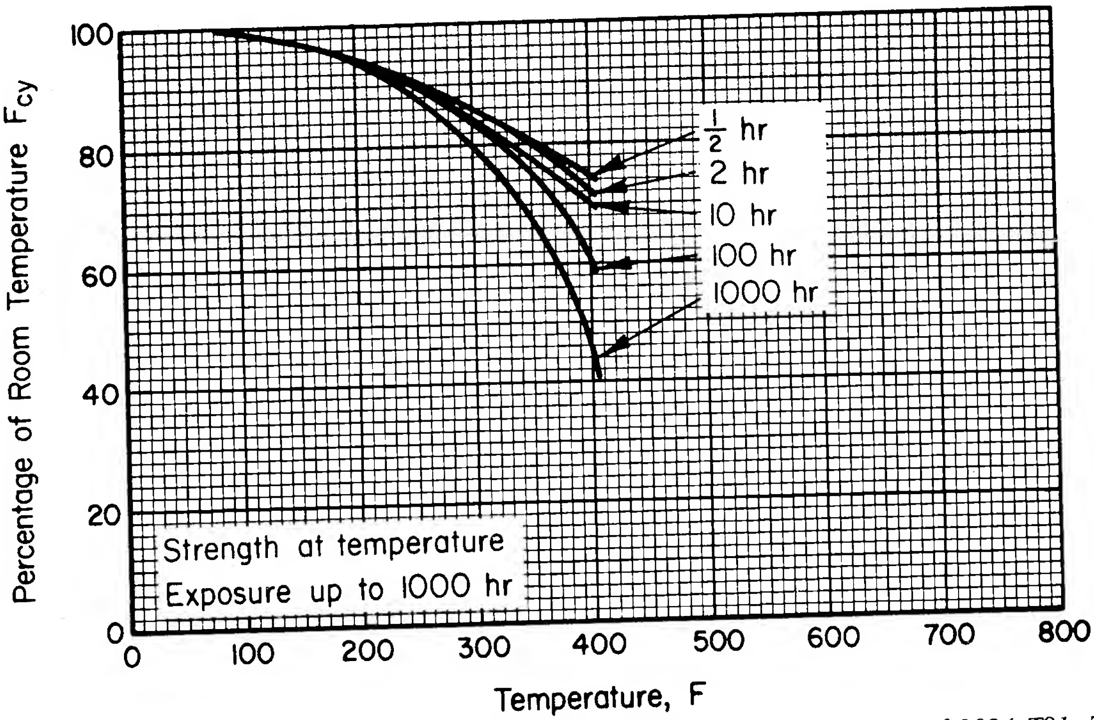

FIGURE 3.2.3.4.2(a). *Effect of temperature on the compressive yield strength (F_{cy}) of 2024-T81, T851, T8510 and T8511 aluminum alloy (all products).*

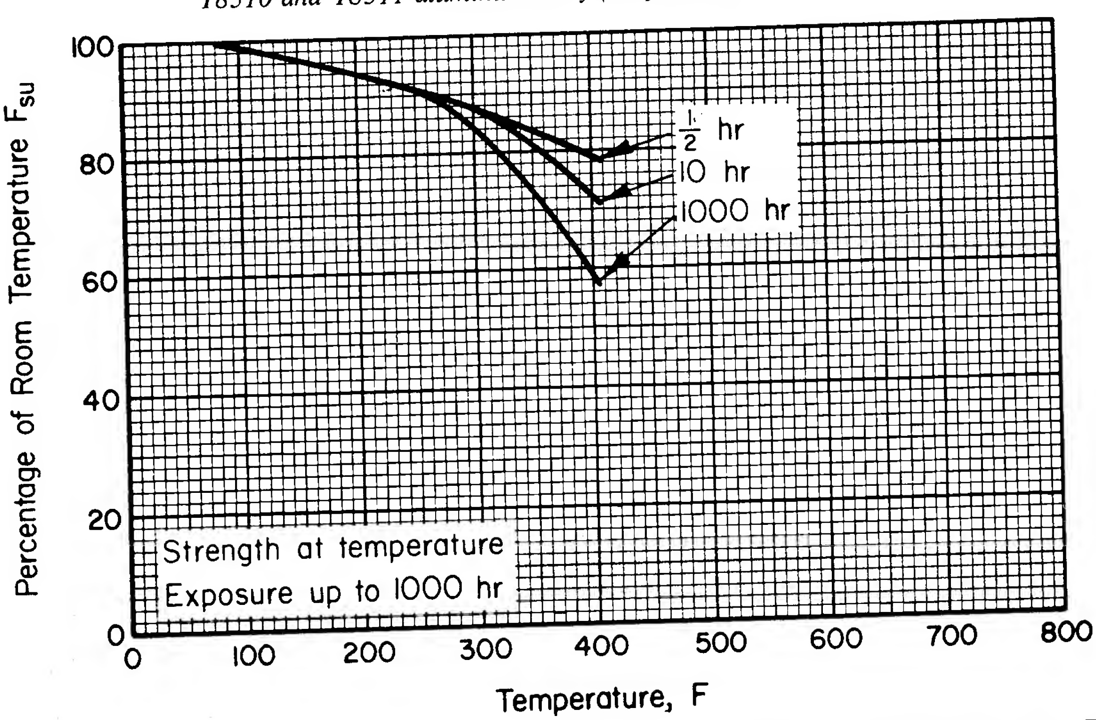

FIGURE 3.2.3.4.2(b). *Effect of temperature on the ultimate shear strength (F_{su}) of 2024-T81, T851, T8510 and T8511 aluminum alloy (all products).*

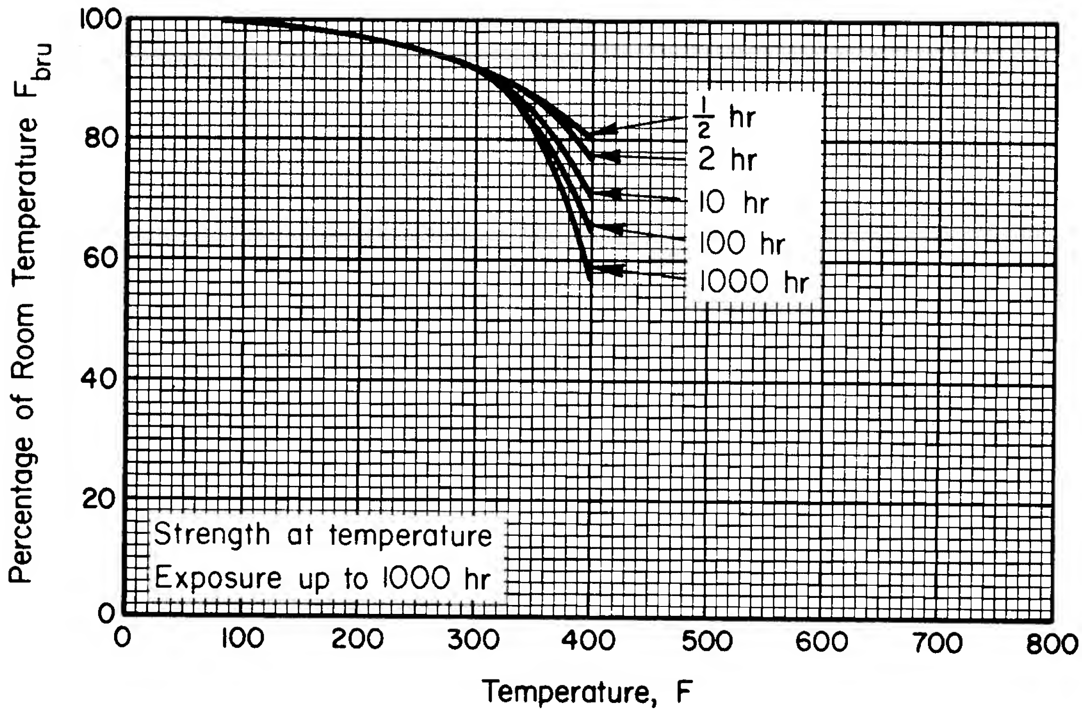

FIGURE 3.2.3.4.3(a). *Effect of temperature on the ultimate bearing strength (F_{bru}) of 2024-T81, T851, T8510 and T8511 aluminum alloy (all products).*

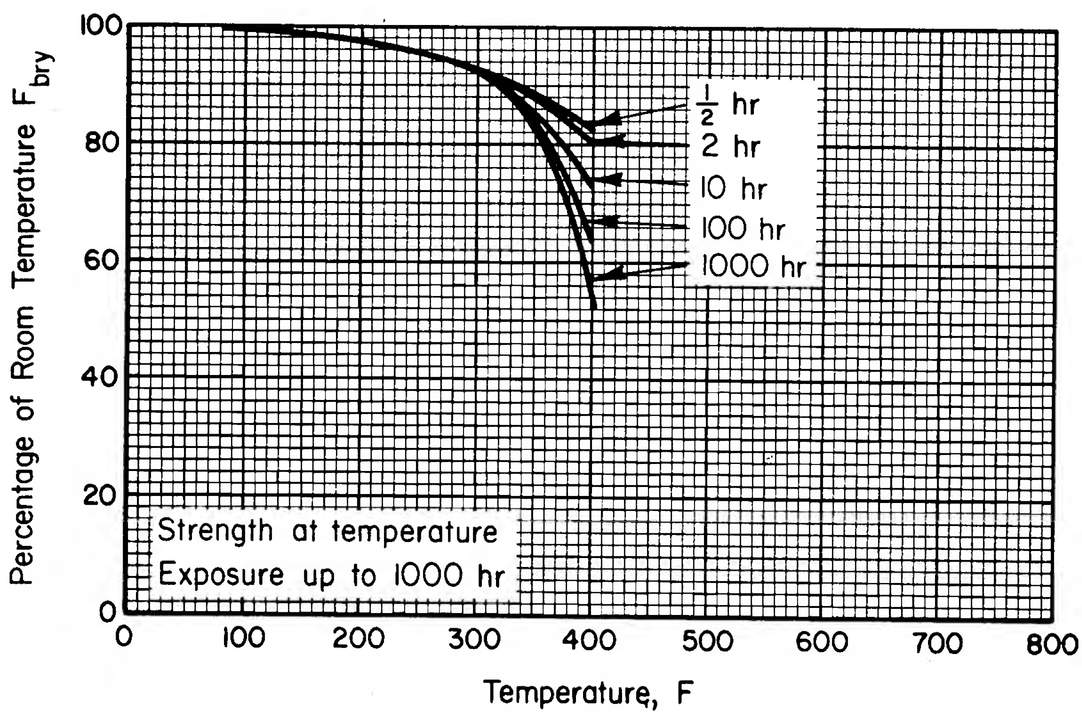

FIGURE 3.2.3.4.3(b). *Effect of temperature on the bearing yield strength (F_{bry}) of 2024-T81, T851, T8510 and T8511 aluminum alloy (all products).*

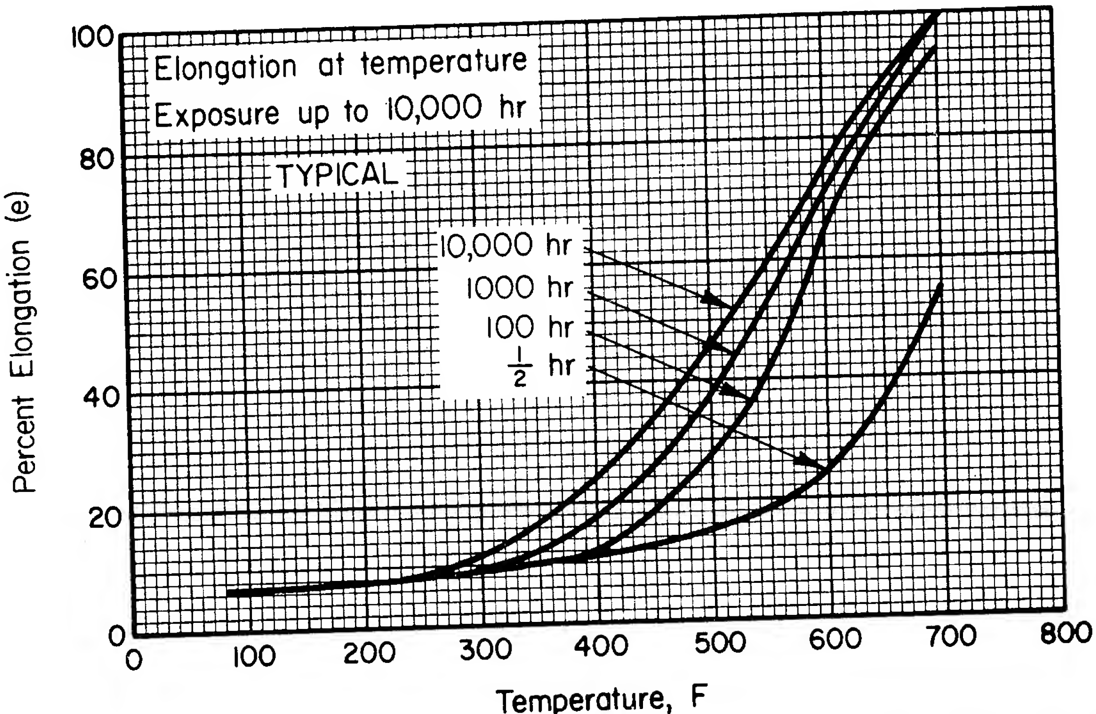

FIGURE 3.2.3.4.5(a). *Effect of temperature on the elongation of 2024-T81, T851, T8510 and T8511 aluminum alloy (all products).*

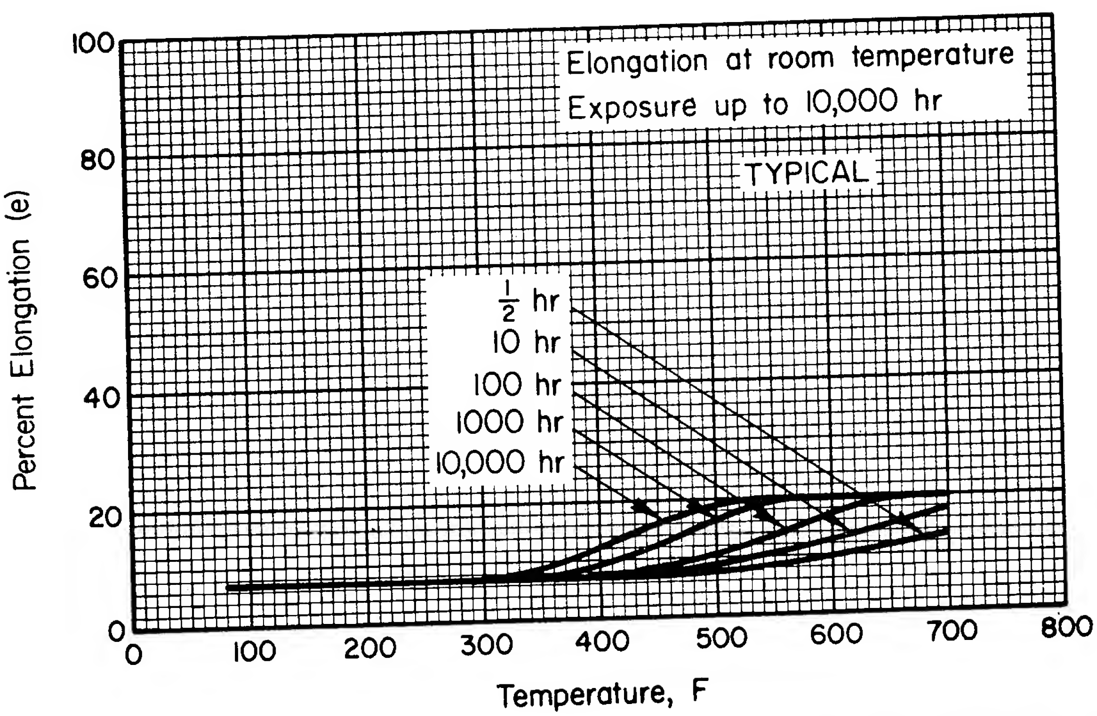

FIGURE 3.2.3.4.5(b). *Effect of exposure at elevated temperatures on the elongation of 2024-T81, T851, T8510 and T8511 aluminum alloy (all products).*

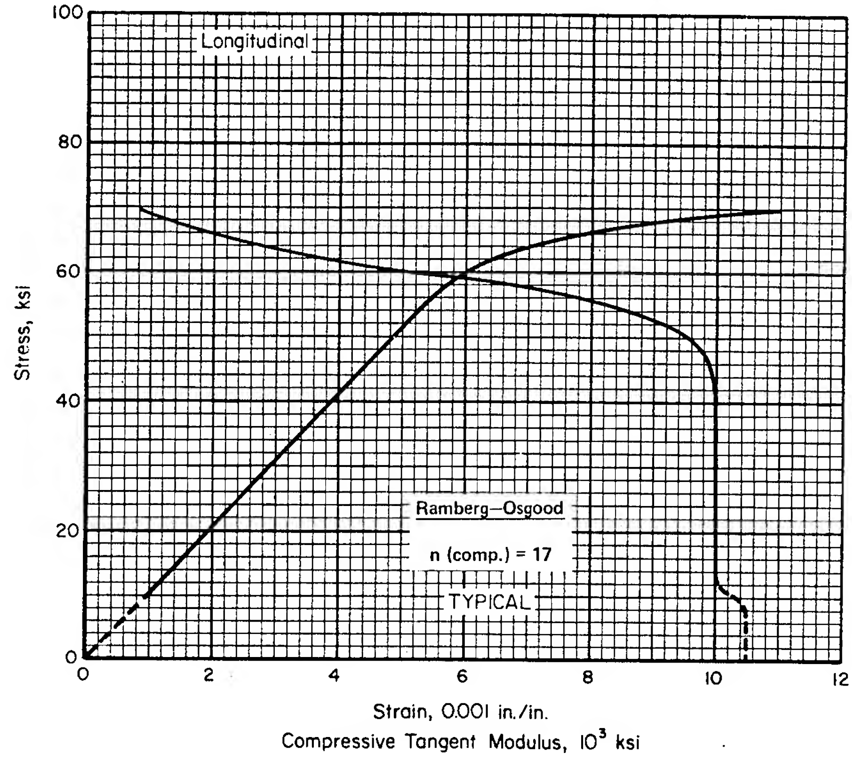

FIGURE 3.2.3.4.6(a). *Typical compressive stress-strain and compressive tangent-modulus curves for clad 2024-T81 aluminum alloy sheet at room temperature.*

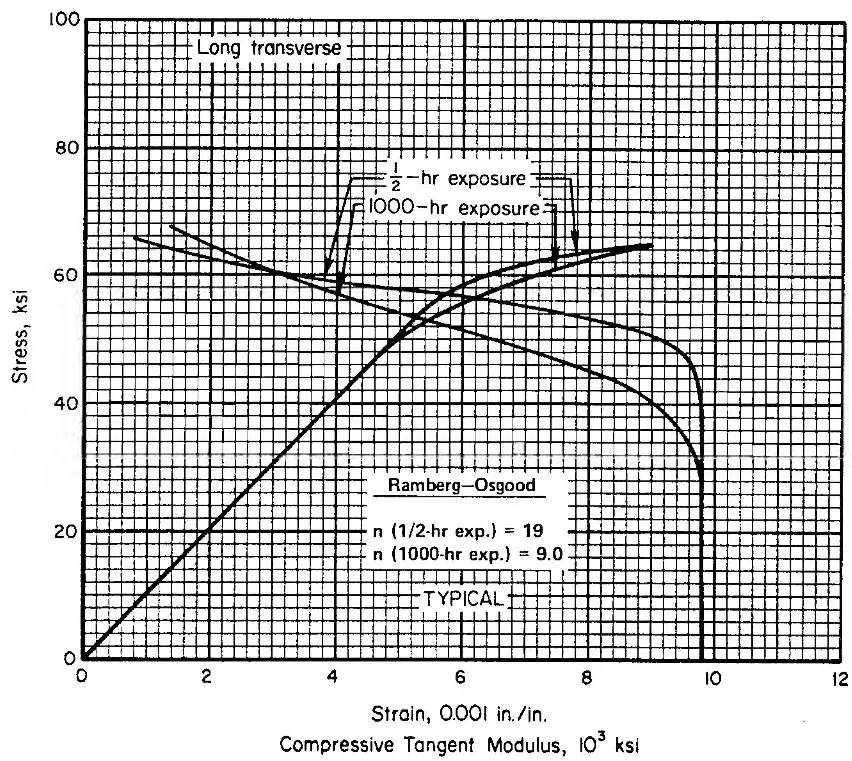

FIGURE 3.2.3.4.6(b). *Typical compressive stress-strain and compressive tangent-modulus curves for clad 2024-T81 aluminum alloy sheet at 200 F.*

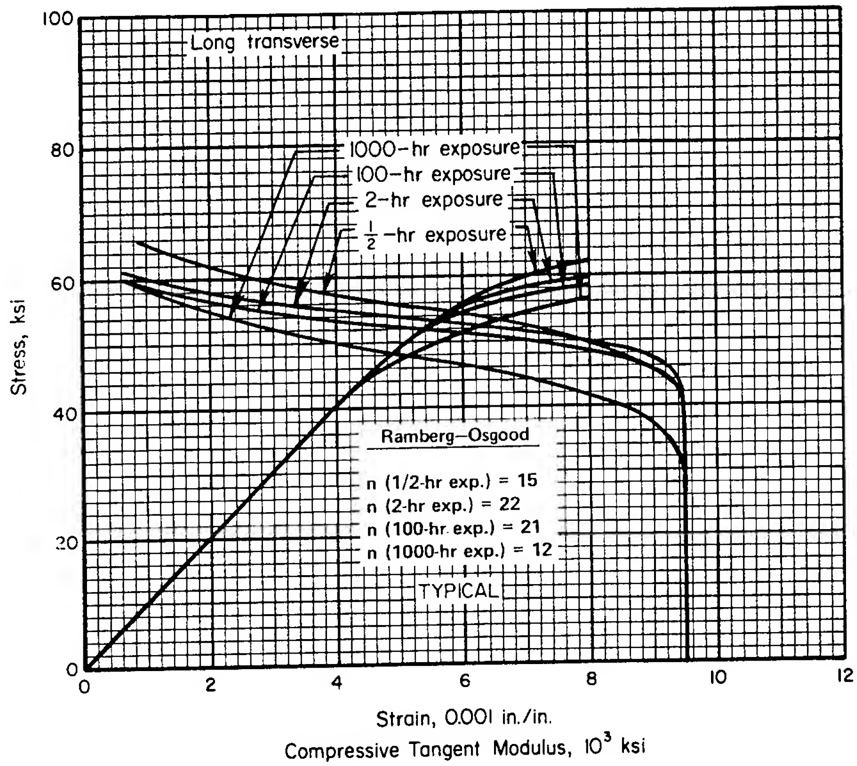

FIGURE 3.2.3.4.6(c). *Typical compressive stress-strain and compressive tangent-modulus curves for clad 2024-T81 aluminum alloy sheet at 300 F.*

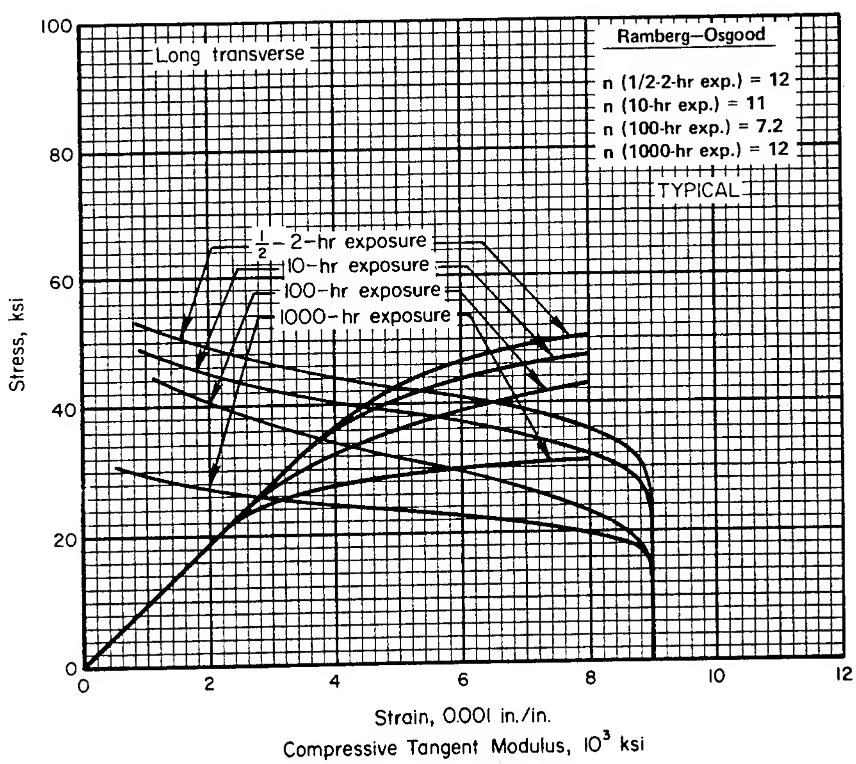

FIGURE 3.2.3.4.6(d). *Typical compressive stress-strain and compressive tangent-modulus curves for clad 2024-T81 aluminum alloy sheet at 400 F.*

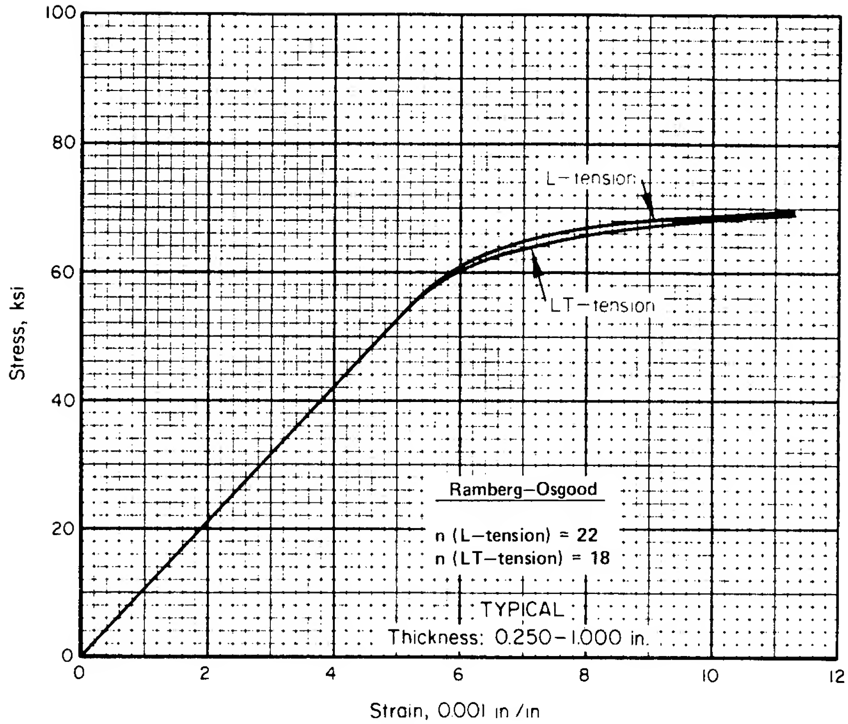

FIGURE 3.2.3.4.6(e). *Typical tensile stress-strain curves for 2024-T851 aluminum alloy plate at room temperature.*

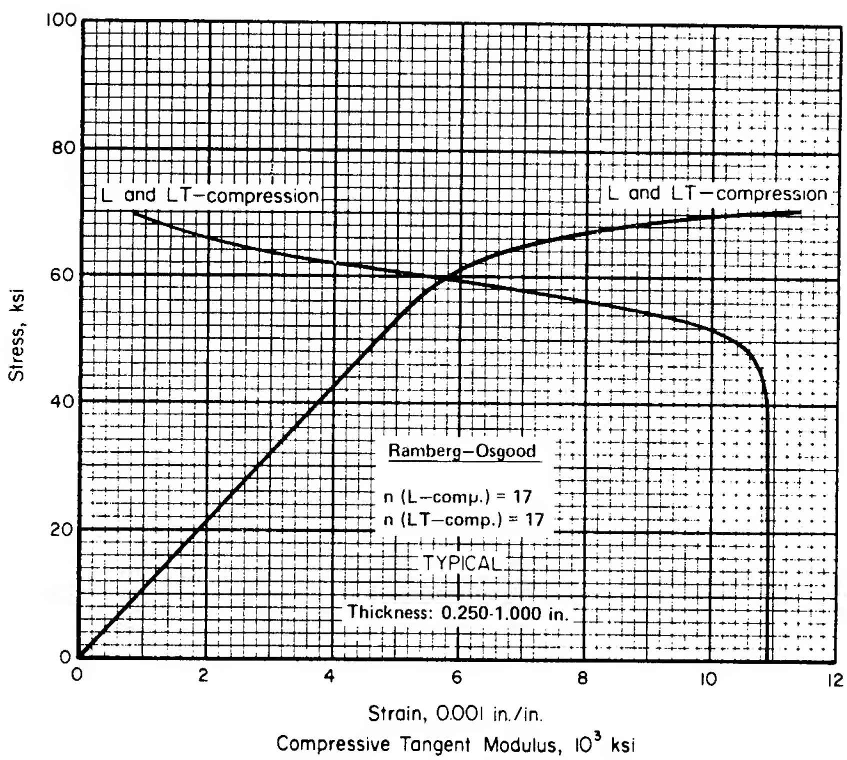

FIGURE 3.2.3.4.6(f). *Typical compressive stress-strain and compressive tangent-modulus curves for 2024-T851 aluminum alloy plate at room temperature.*

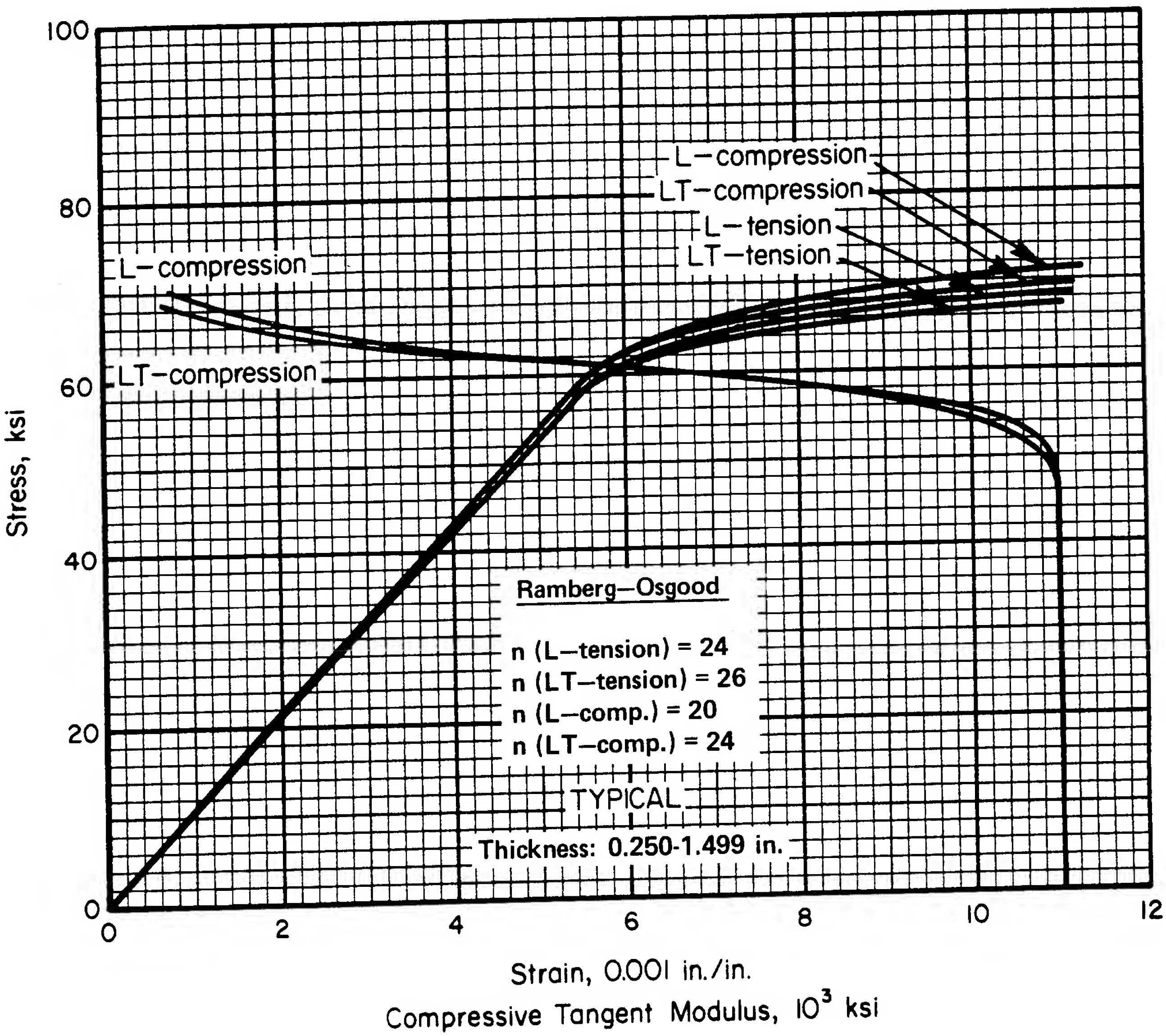

FIGURE 3.2.3.4.6(g). *Typical tensile and compressive stress-strain and compressive tangent-modulus curves for 2024-T851X aluminum alloy extrusion at room temperature.*

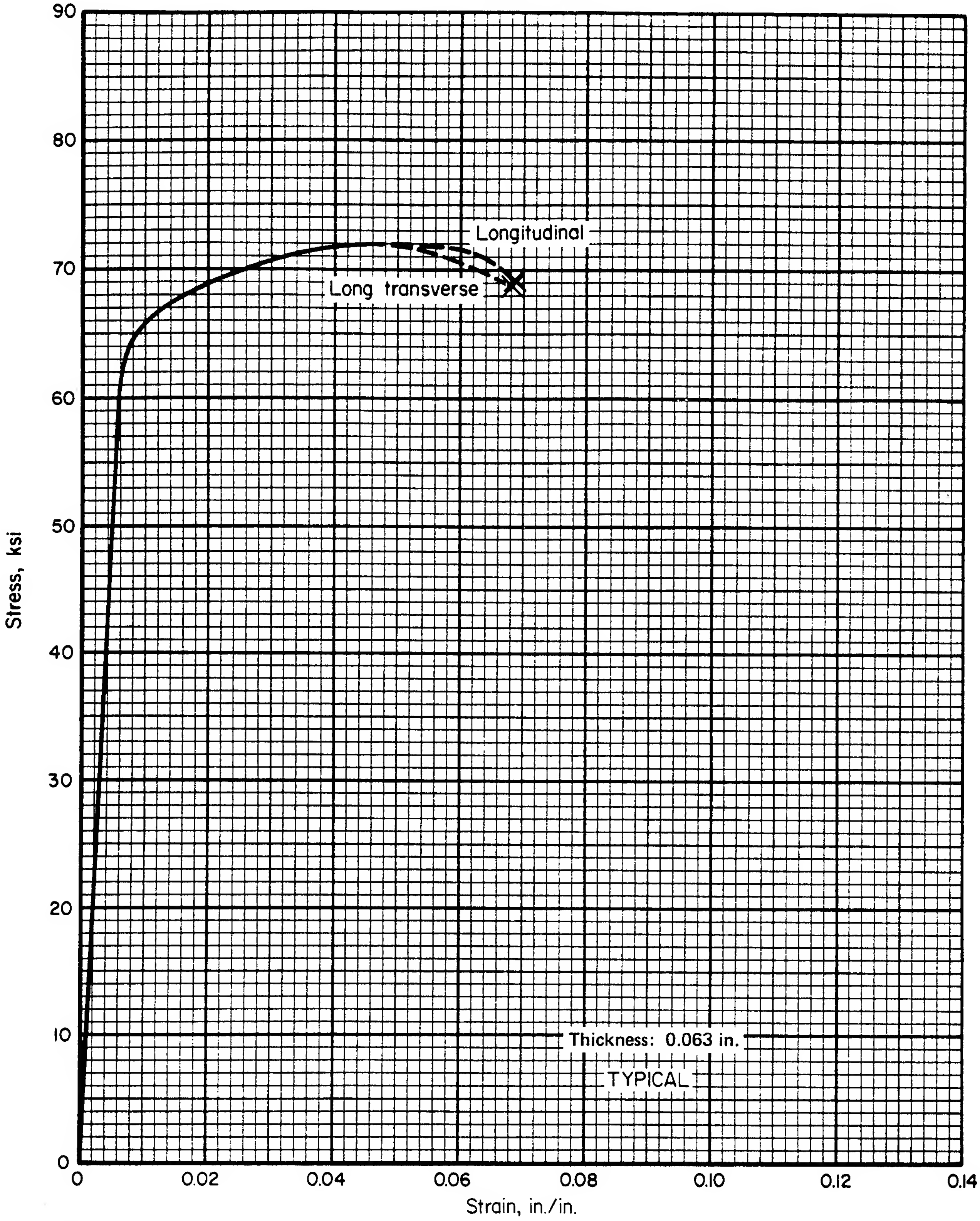

FIGURE 3.2.3.4.6(h). *Typical tensile stress-strain curves (full range) for 2024-T81 aluminum alloy sheet at room temperature.*

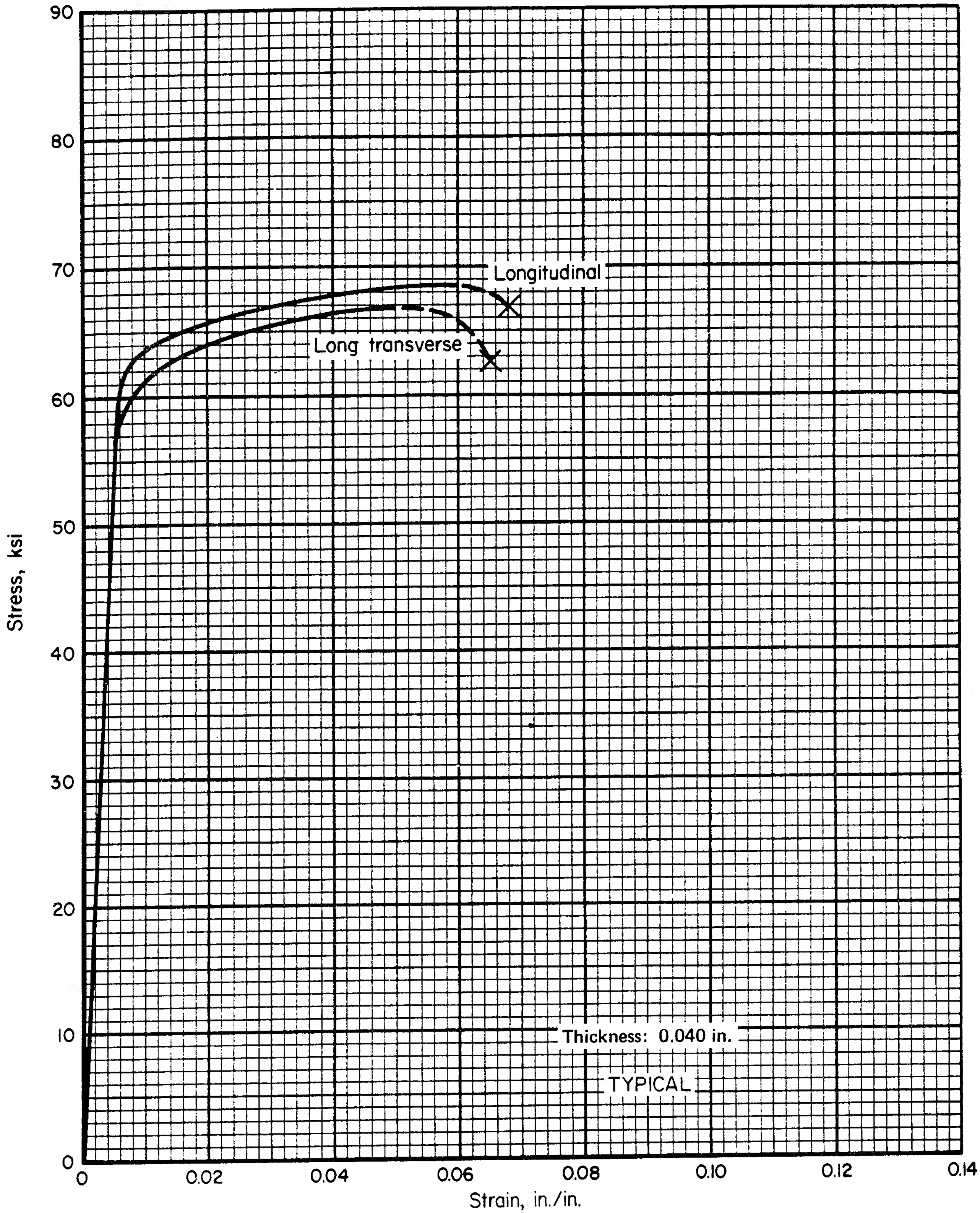

FIGURE 3.2.3.4.6(i). *Typical tensile stress-strain curves (full range) for clad 2024-T81 aluminum alloy sheet at room temperature.*

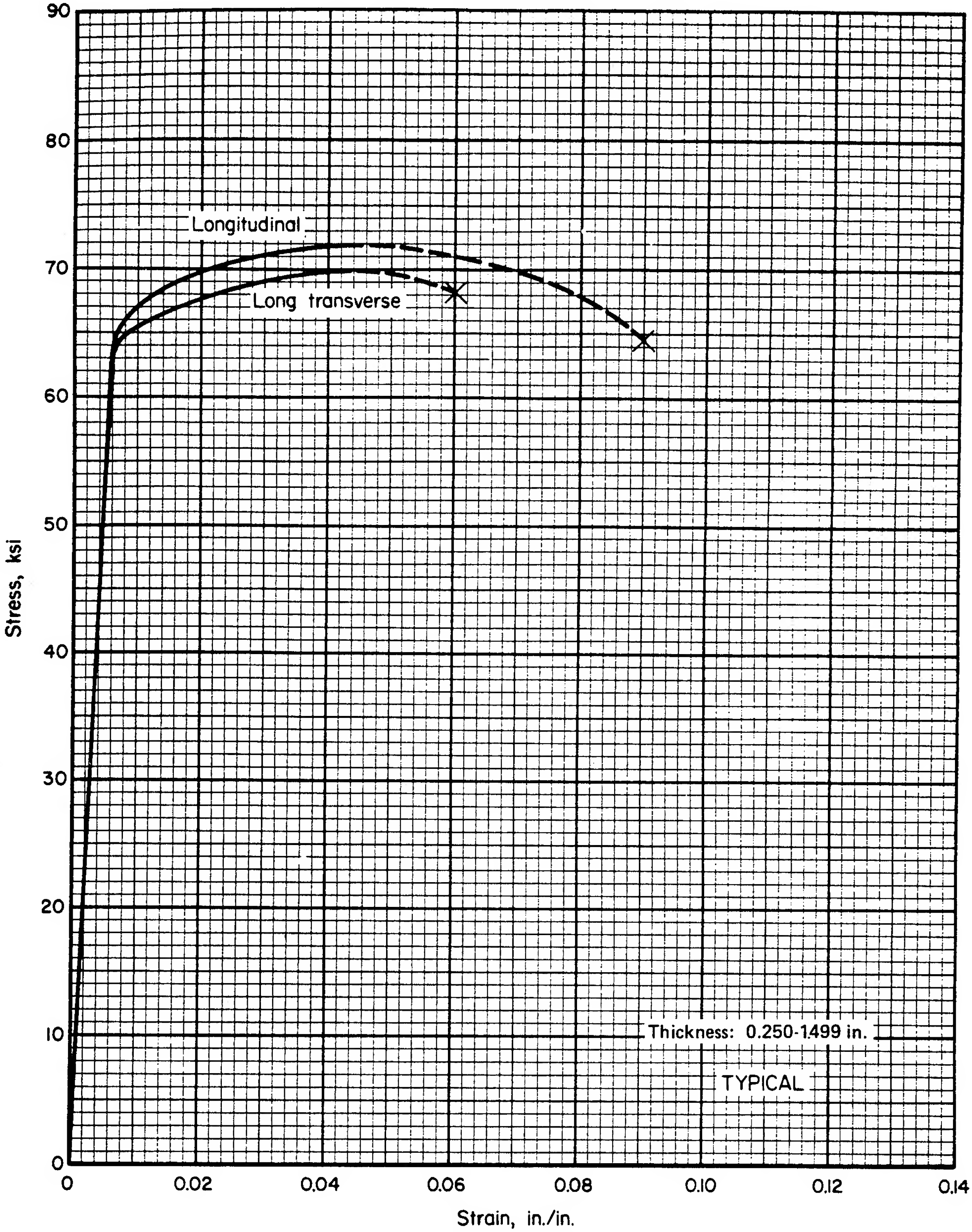

FIGURE 3.2.3.4.6(j). *Typical tensile stress-strain curves (full range) for 2024-T851 aluminum alloy sheet at room temperature.*

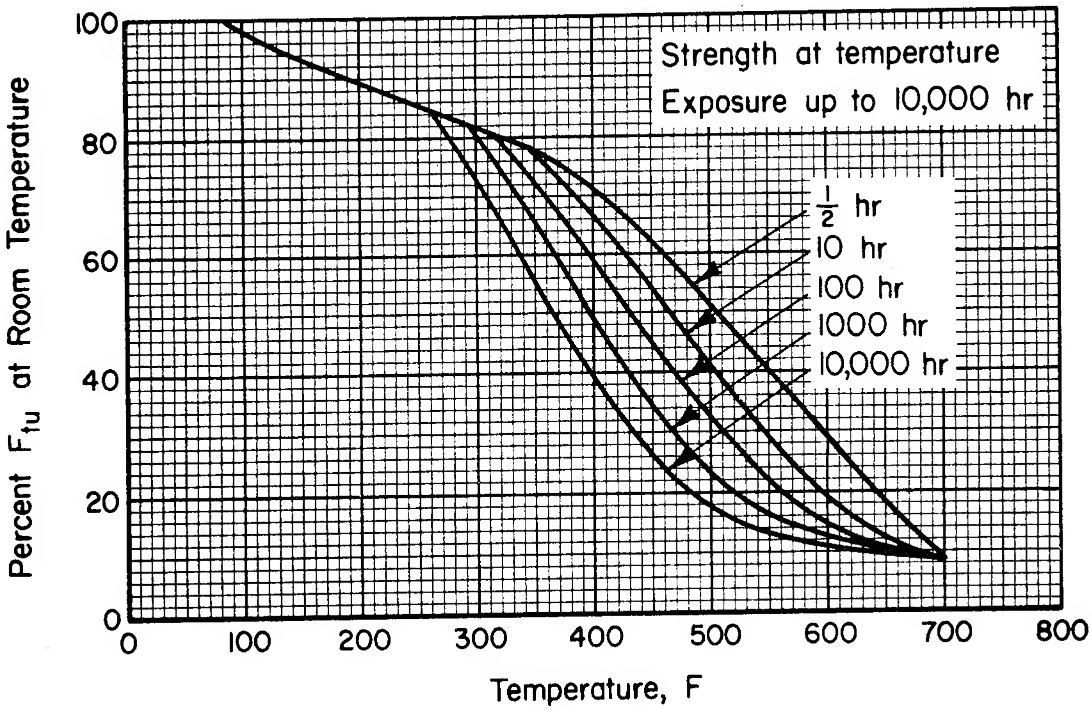

FIGURE 3.2.3.5.1(a). *Effect of temperature on the tensile ultimate strength (F_{tu}) of 2024-T861 (T86) aluminum alloy sheet.*

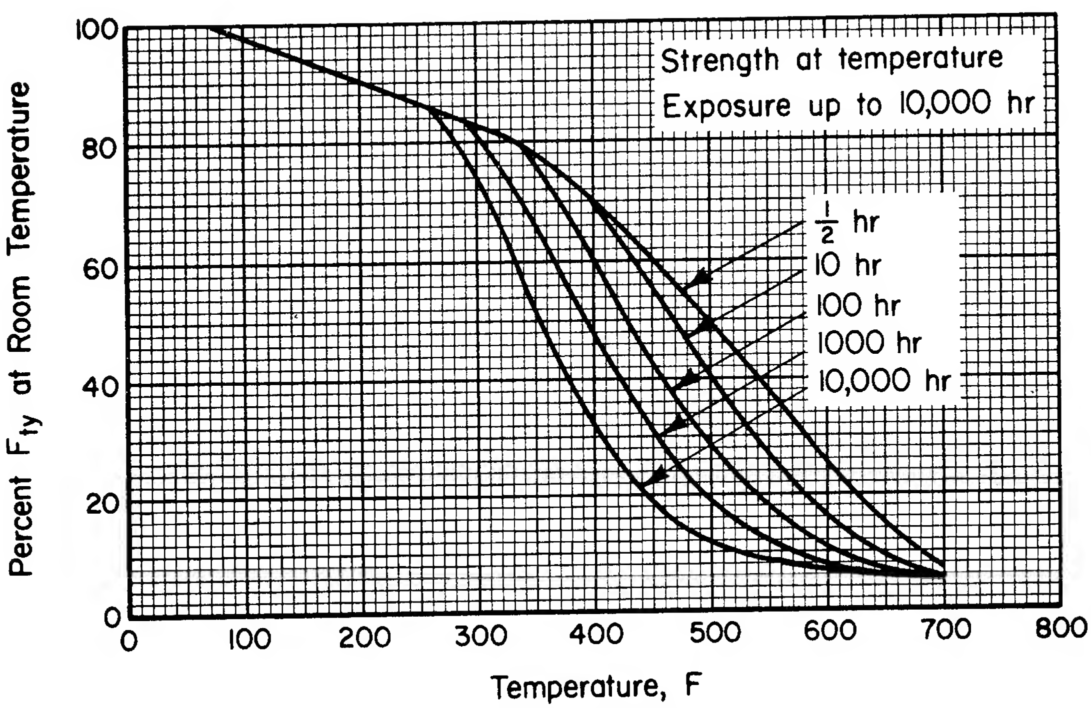

FIGURE 3.2.3.5.1(b). *Effect of temperature on the tensile yield strength (F_{ty}) of 2024-T861 (T86) aluminum alloy sheet.*

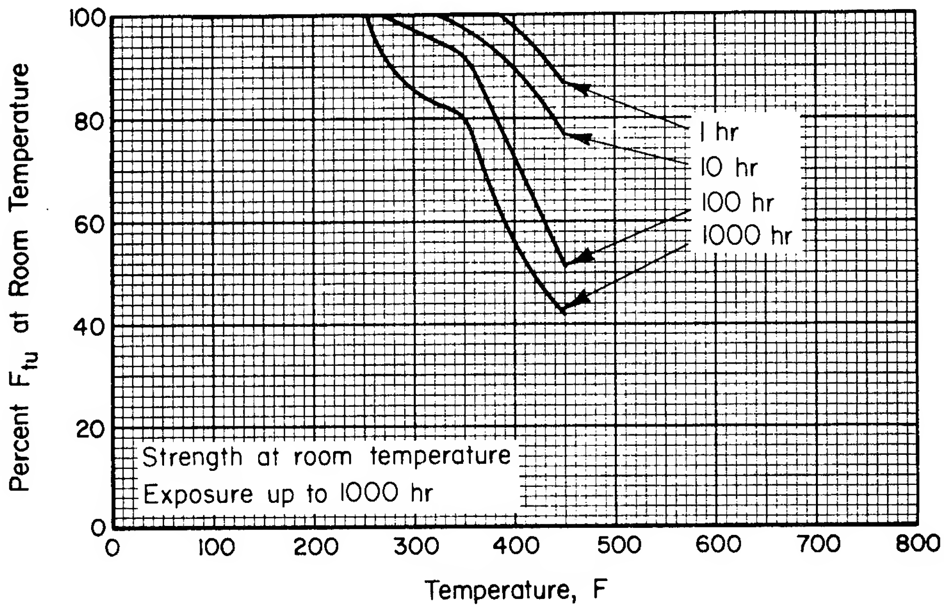

FIGURE 3.2.3.5.1(c). *Effect of exposure at elevated temperatures on the room-temperature tensile ultimate strength (F_{tu}) of 2024-T861 (T86) aluminum alloy sheet.*

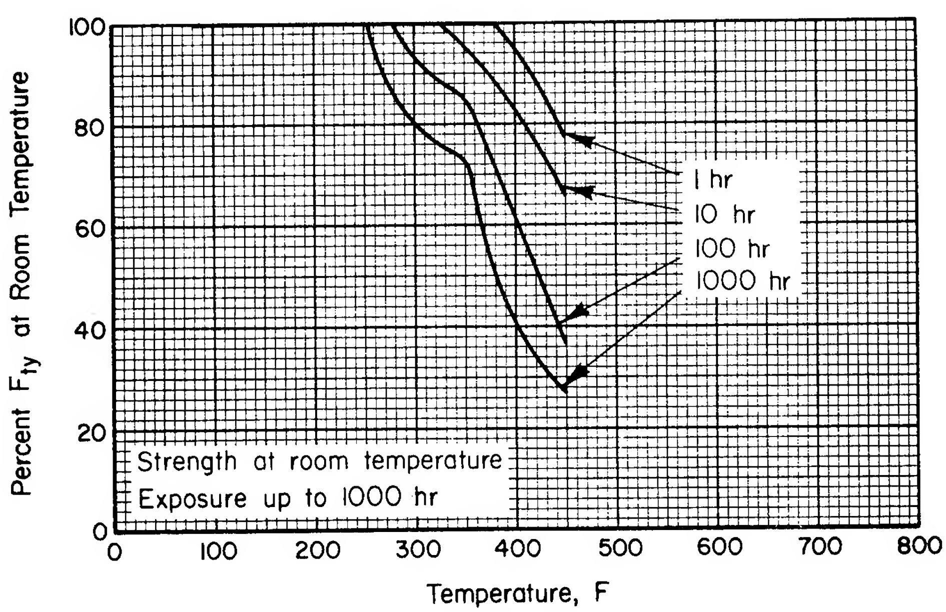

FIGURE 3.2.3.5.1(d). *Effect of exposure at elevated temperatures on the room-temperature tensile yield strength (F_{ty}) of 2024-T861 (T86) aluminum alloy sheet.*

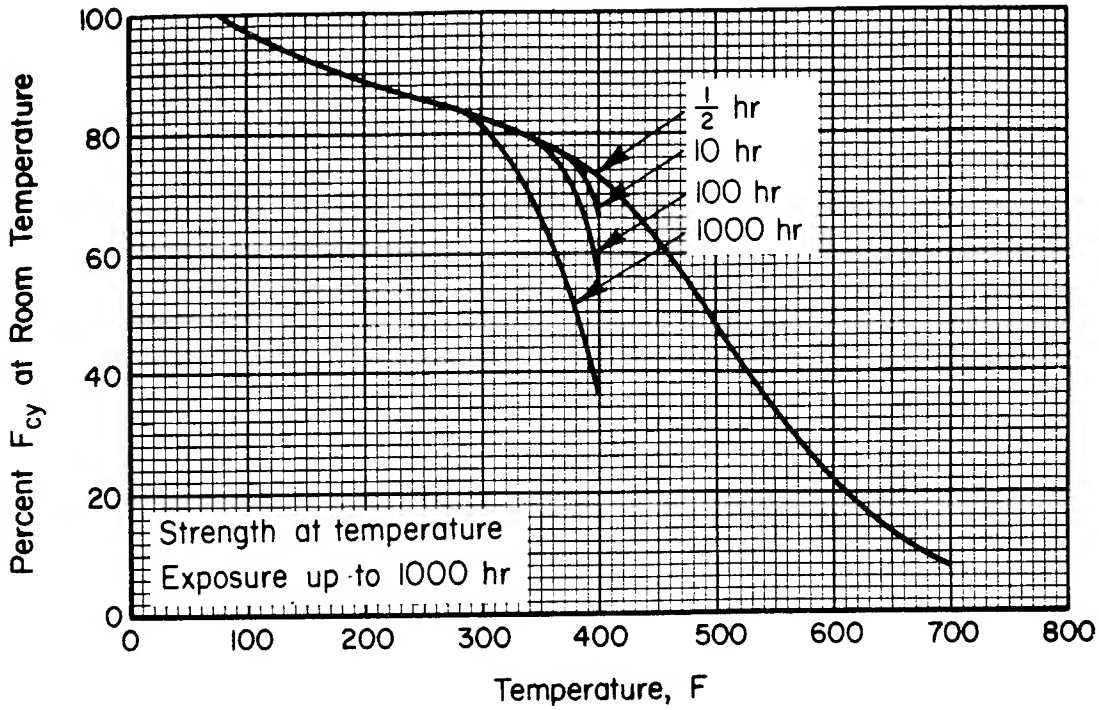

FIGURE 3.2.3.5.2(a). *Effect of temperature on the compressive yield strength (F_{cy}) of 2024-T861 (T86) aluminum alloy sheet.*

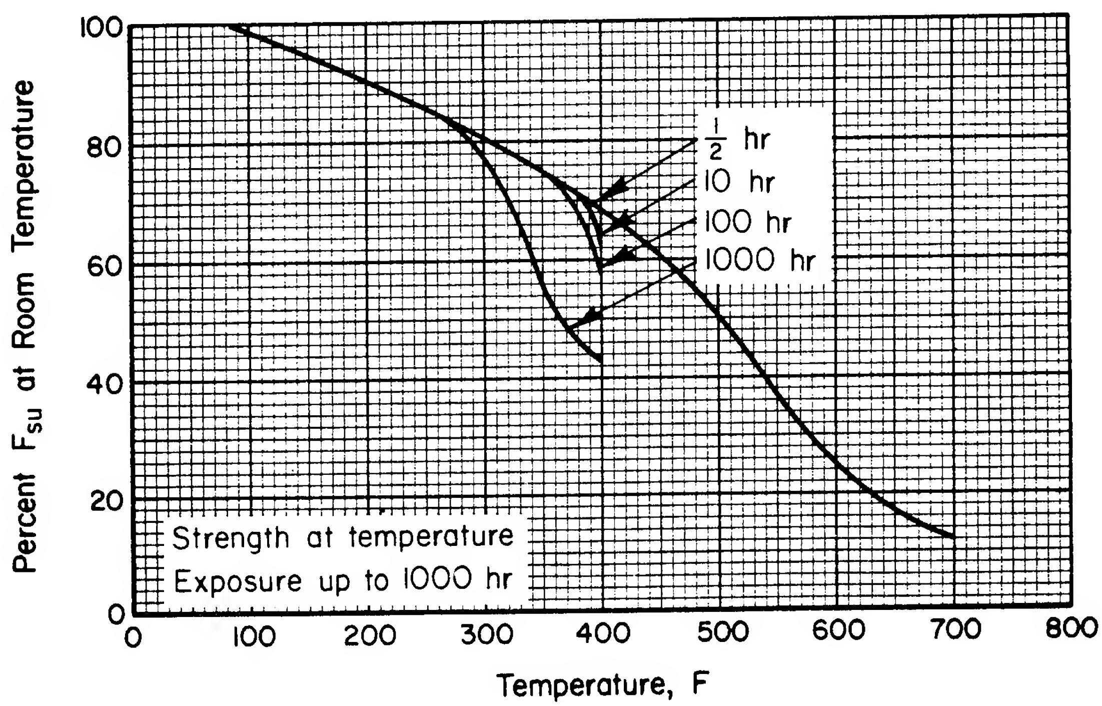

FIGURE 3.2.3.5.2(b). *Effect of temperature on the shear ultimate strength (F_{su}) of 2024-T861 (T86) aluminum alloy sheet.*

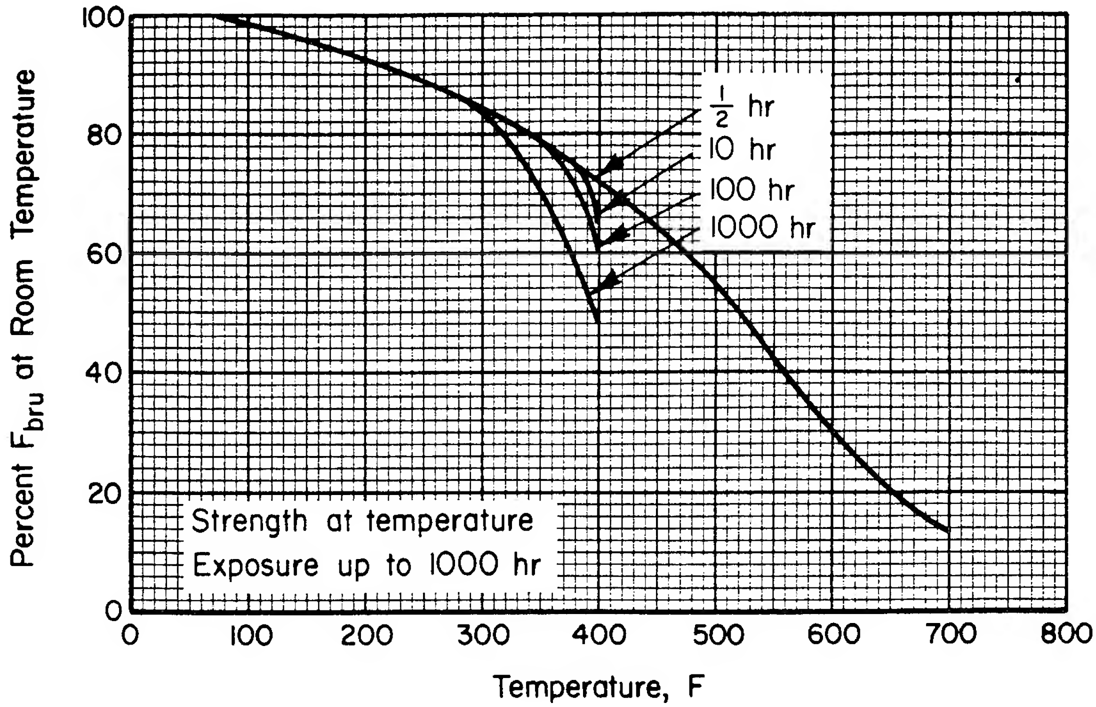

FIGURE 3.2.3.5.3(a). *Effect of temperature on the bearing ultimate strength (F_{bru}, $e/D = 1.5$) of 2024-T861 (T86) aluminum alloy sheet.*

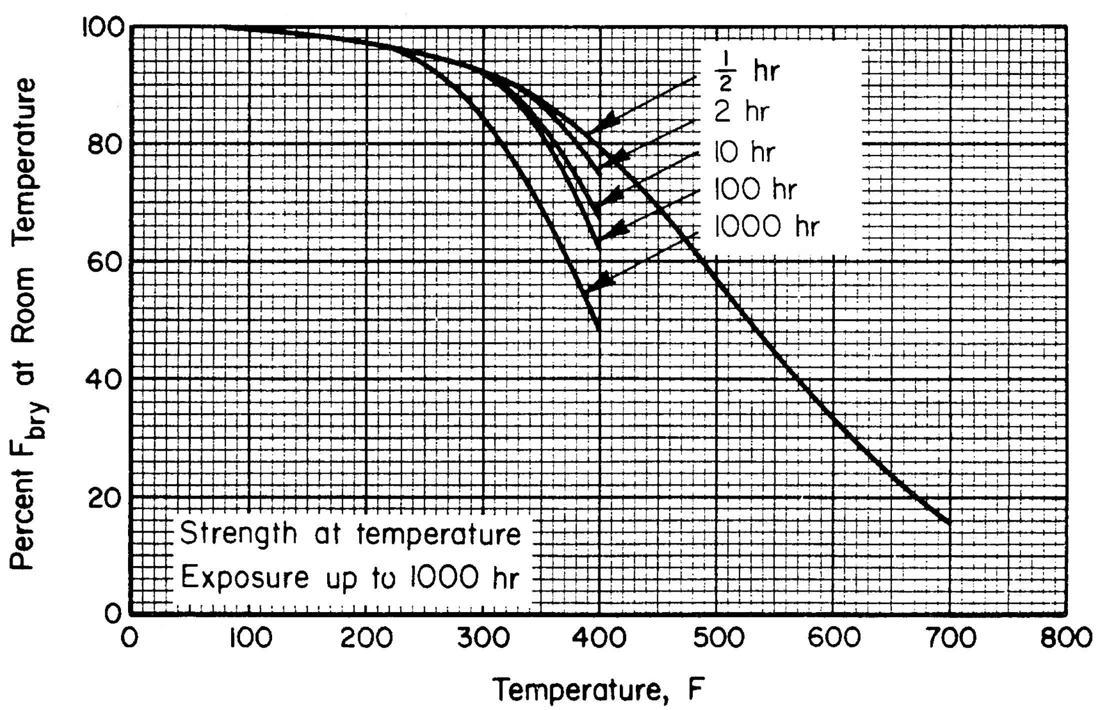

FIGURE 3.2.3.5.3(b). *Effect of temperature on the bearing yield strength (F_{bry}, $e/D = 1.5$) of 2024-T861 (T86) aluminum alloy sheet.*

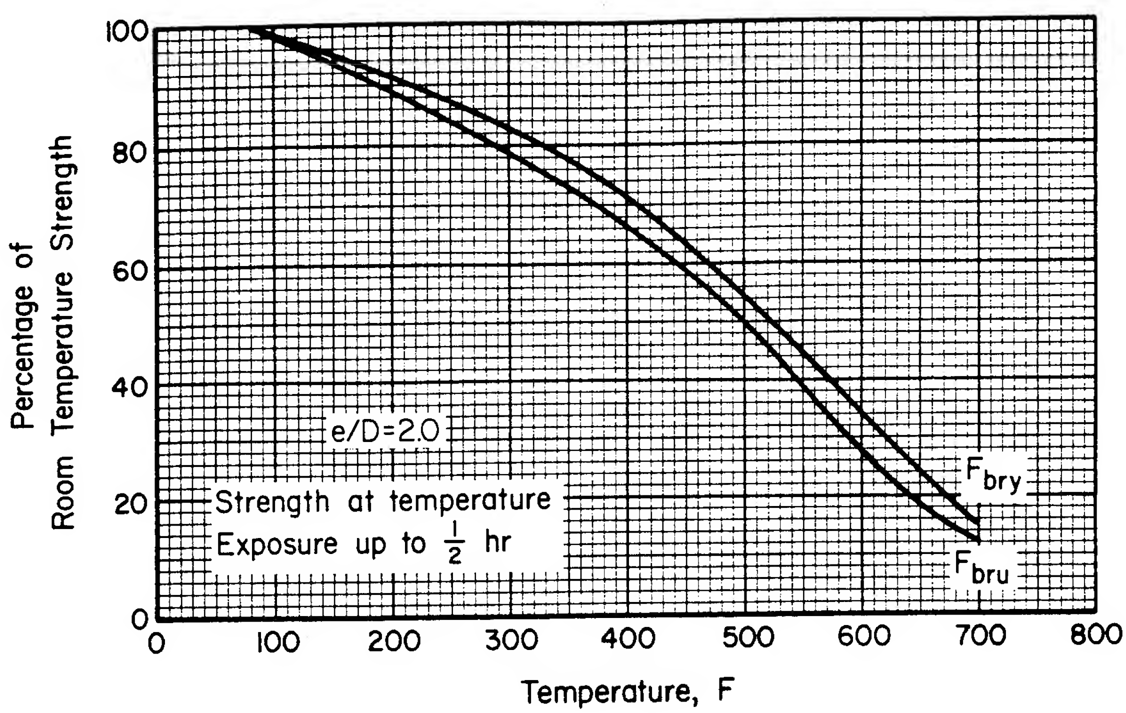

FIGURE 3.2.3.5.3(c). *Effect of temperature on the bearing ultimate strength (F_{bru}, e/D = 2.0) and the bearing yield strength (F_{bry}, e/D = 2.0) of 2024-T861 (T86) aluminum alloy sheet.*

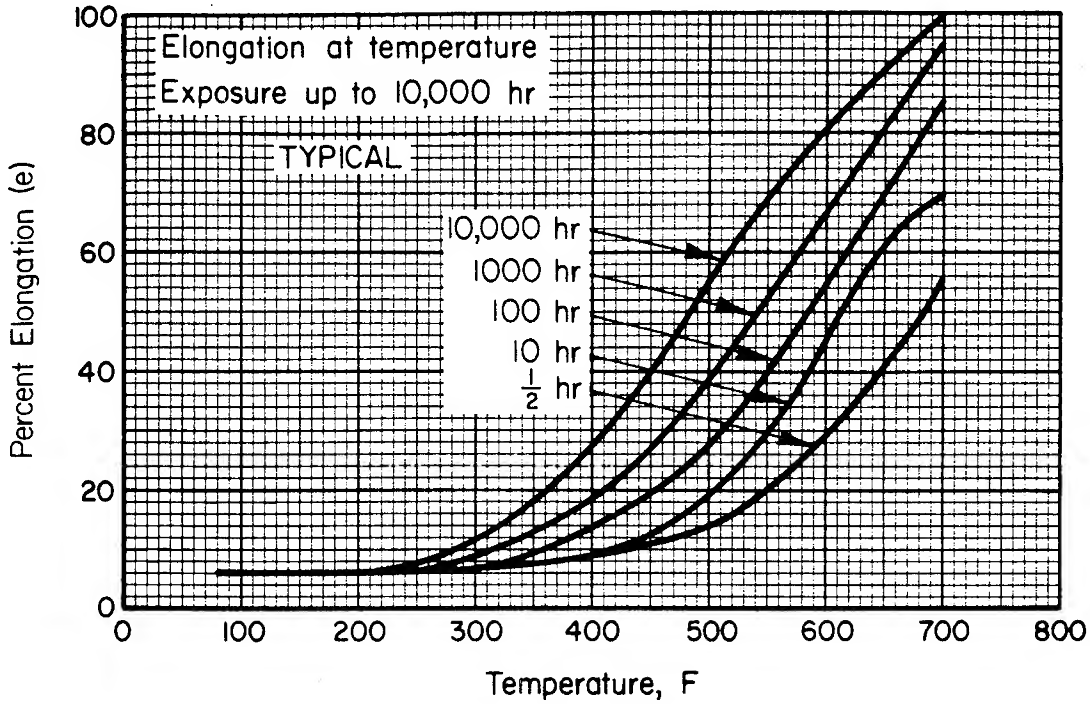

FIGURE 3.2.3.5.5(a). *Effect of temperature on the elongation (e) of 2024-T861 (T86) aluminum alloy sheet.*

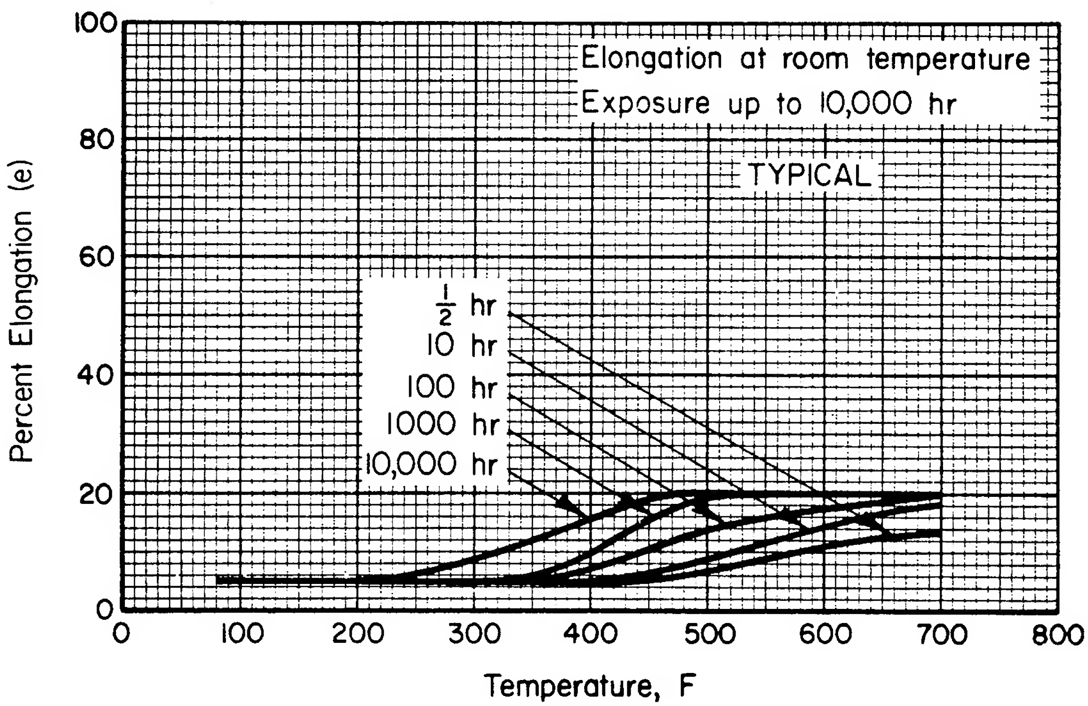

FIGURE 3.2.3.5.5(b). *Effect of exposure at elevated temperatures on the elongation (e) of 2024-T861 (T86) aluminum alloy sheet.*

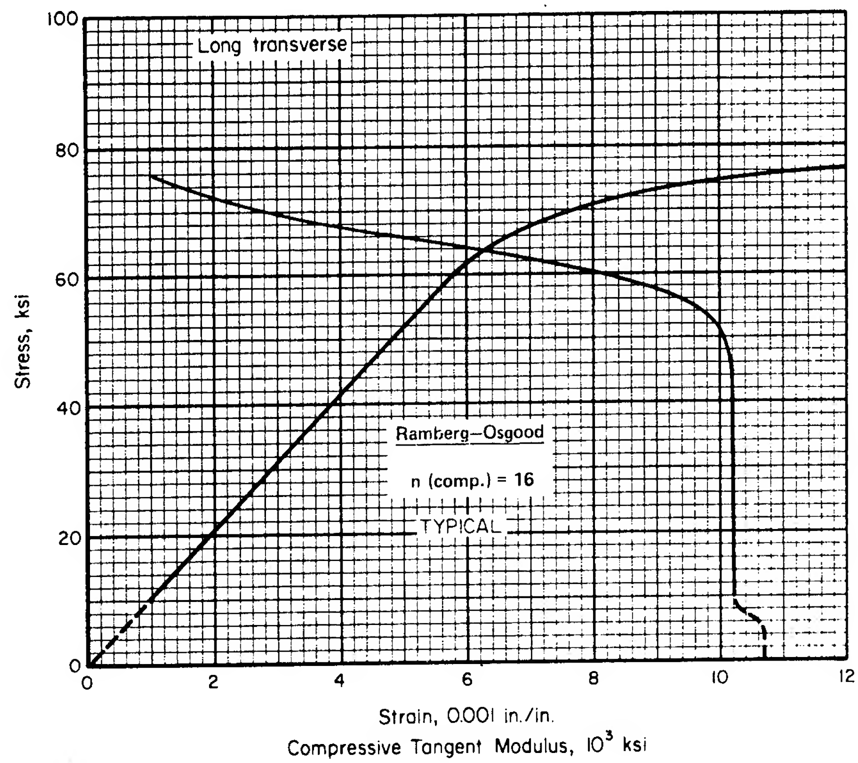

FIGURE 3.2.3.5.6(a). *Typical compressive stress-strain and compressive tangent-modulus curves for clad 2024-T861 aluminum alloy sheet at room temperature.*

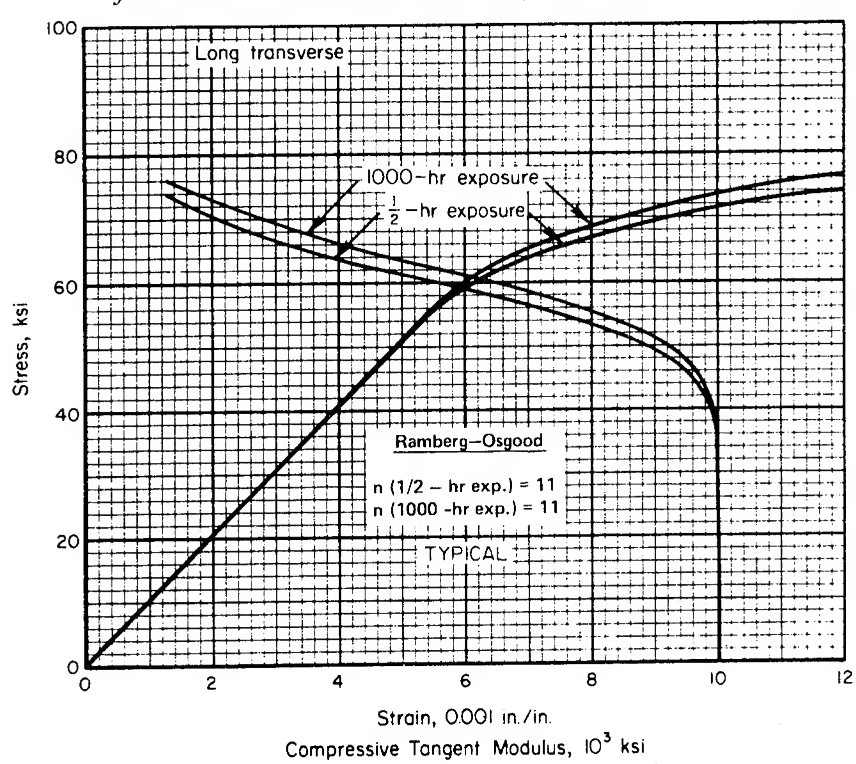

FIGURE 3.2.3.5.6(b). *Typical compressive stress-strain and compressive tangent-modulus curves for clad 2024-T861 aluminum alloy sheet at 200 F.*

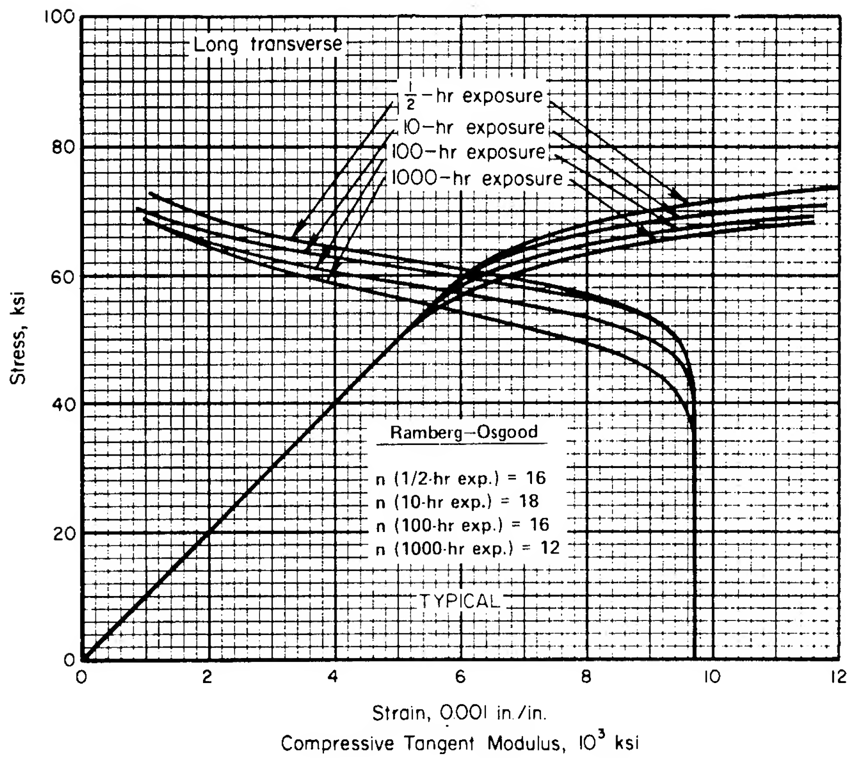

FIGURE 3.2.3.5.6(c). *Typical compressive stress-strain and compressive tangent-modulus curves for clad 2024-T861 aluminum alloy sheet at 300 F.*

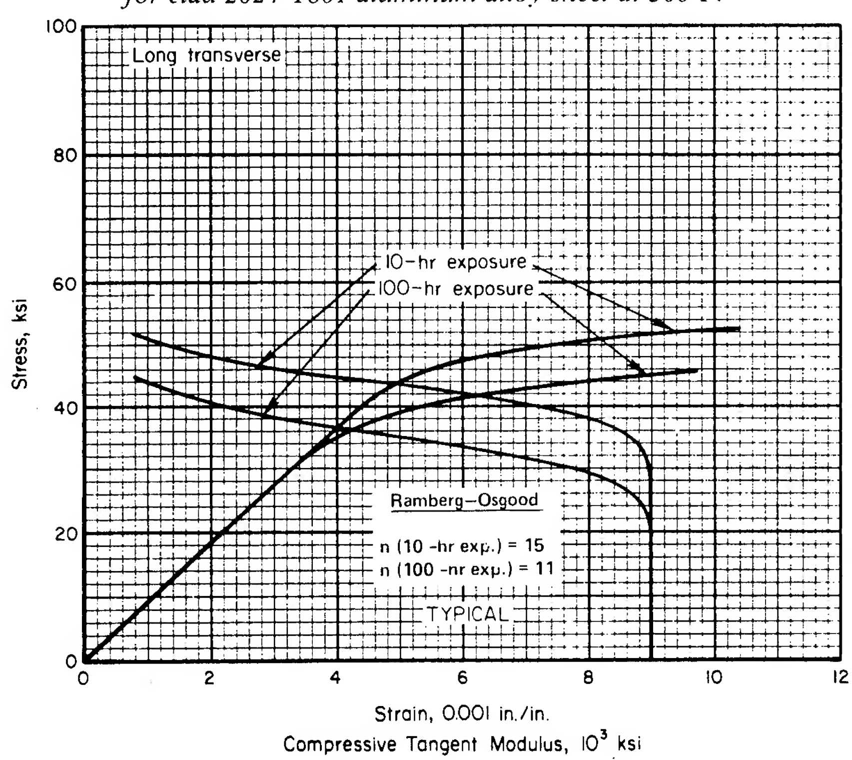

FIGURE 3.2.3.5.6(d). *Typical compressive stress-strain and compressive tangent-modulus curves for clad 2024-T861 aluminum alloy sheet at 400 F.*

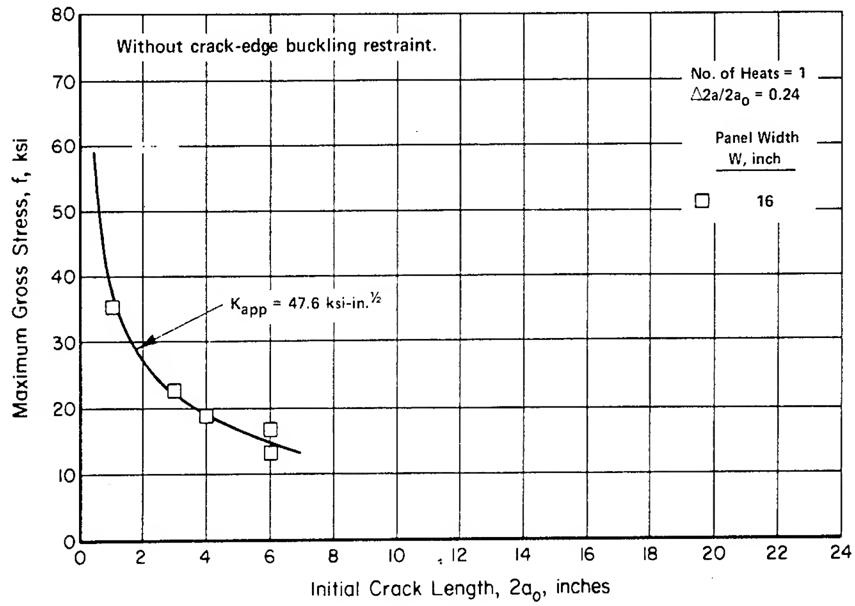

FIGURE 3.2.3.5.10(a). *Residual strength behavior of 0.063-inch-thick 2024-T861 aluminum alloy sheet at room temperature. Crack orientation is T-L.* [*Reference 3.1.2.1.6(d)*].

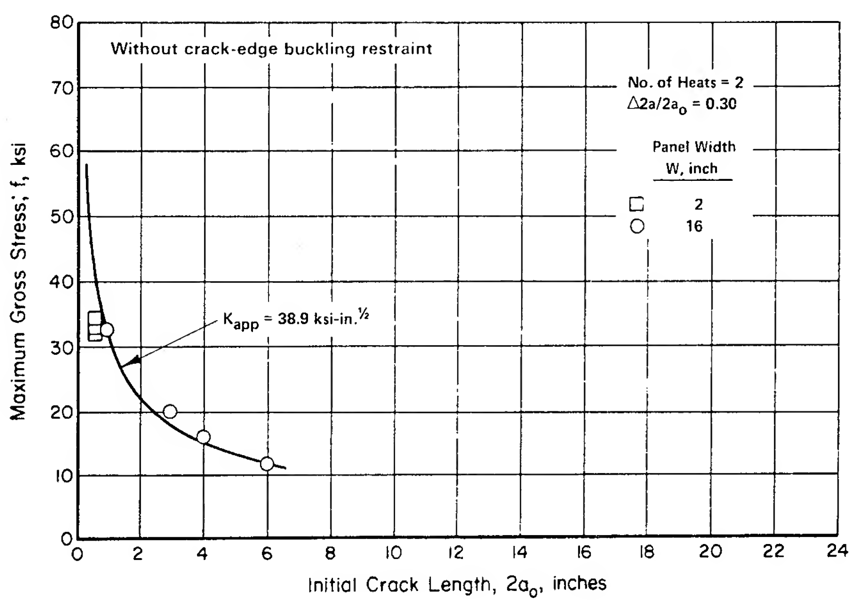

FIGURE 3.2.3.5.10(b). *Residual strength behavior of 0.063-inch-thick 2024-T861 aluminum alloy sheet at room temperature. Crack orientation is L-T.* [*Reference 3.1.2.1.6(d)*].

3.2.4 2025 ALLOY

3.2.4.0 *Comments and Properties.*—2025 is a heat-treatable Al-Cu forging alloy for which applications have been limited primarily to propellers. Refer to Section 3.1.2.3 for comments regarding the resistance of the alloy to stress-corrosion cracking, and to Section 3.1.2.4 for comments regarding the weldability of the alloy.

A material specification for 2025 aluminum alloy is presented in Table 3.2.4.0(a). Room-temperature mechanical and physical properties are shown in Table 3.2.4.0(b). The effect of temperature on thermal expansion is shown in Figure 3.2.4.0.

TABLE 3.2.4.0(a). *Material Specification for 2025 Aluminum Alloy*

Specification	Form
AMS 4130	Die forging

TABLE 3.2.4.0(b). *Design Mechanical and Physical Properties of 2025 Aluminum Alloy Die Forging*

Specification	AMS 4130
Form	Die forging
Temper	T6
Thickness, in.	≤ 4.000
Basis	S
Mechanical Properties:	
F_{tu}, ksi:	
L	55
T[a]	52
F_{ty}, ksi:	
L	33
T[a]	32
F_{cy}, ksi:	
L	...
T[a]	...
F_{su}, ksi	...
F_{bru}, ksi:	
(e/D = 1.5)	...
(e/D = 2.0)	...
F_{bry}, ksi:	
(e/D = 1.5)	...
(e/D = 2.0)	...
e, percent:	
L	11
T[a]	8
E, 10^3 ksi	10.3
E_c, 10^3 ksi	10.5
G, 10^3 ksi	3.9
μ	0.33
Physical Properties:	
ω, lb/in.^{3}	0.101
C, Btu/(lb)(F)	0.23 (at 212 F)
K, Btu/[(hr)(ft^2)(F)/ft]	90 (at 77 F)
α, 10^{-6} in./in./F	See Figure 3.2.4.0

[a]For die forgings, T indicates any grain direction not within ± 15° of being parallel to the forging flow lines. Specimens to test transverse properties should be located as close to the short transverse direction as possible.

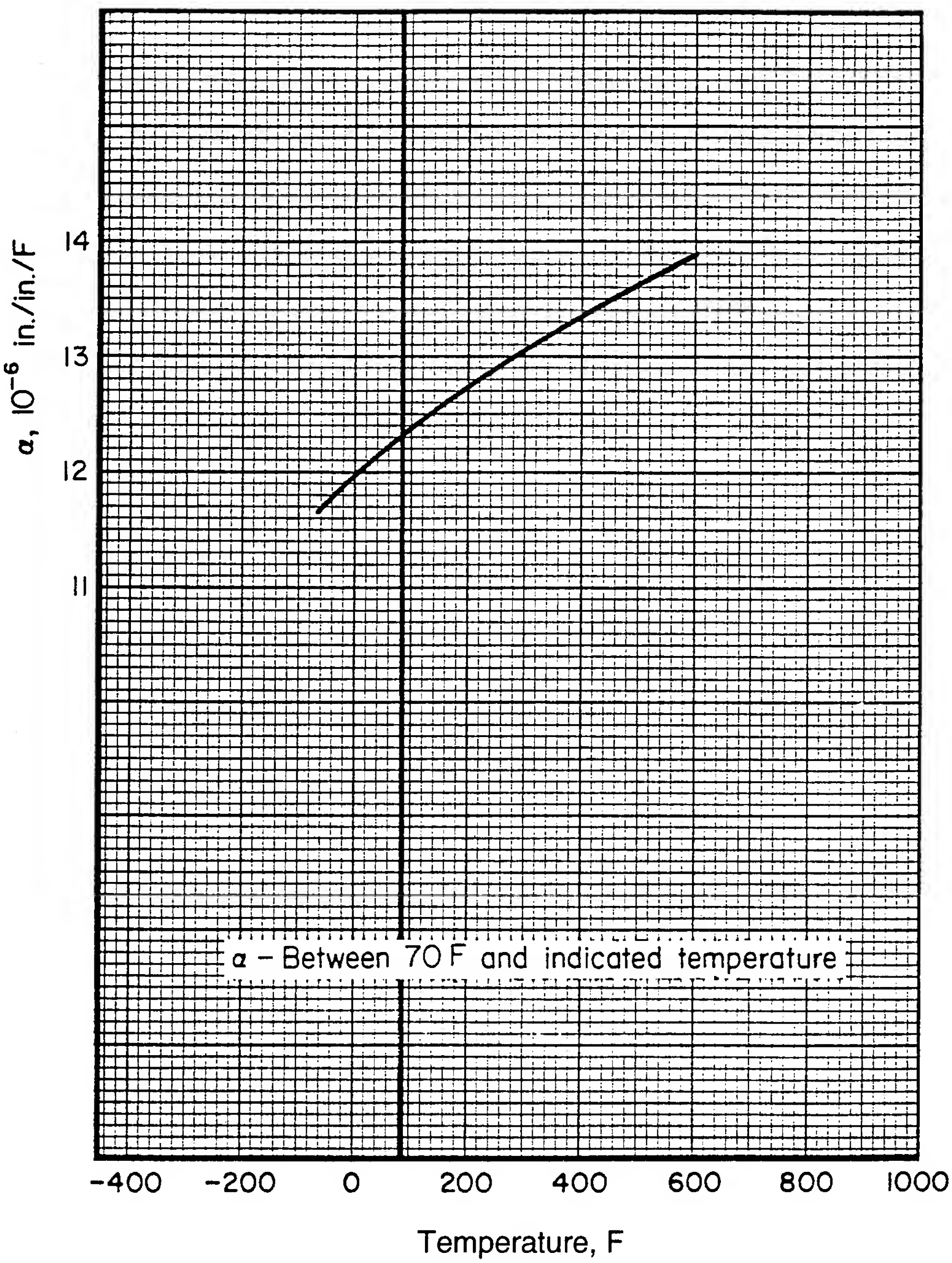

FIGURE 3.2.4.0. *Effect of temperature on the thermal expansion of 2025 aluminum alloy.*

3.2.5 2090 ALLOY

3.2.5.0 *Comments and Properties.*—2090 is an Al-Cu-Li alloy developed for applications requiring the high strength of 7075-T6 but with 8 percent lower density and 10 percent higher elastic modulus than 7075-T6. Sheet is available in the T83 temper. 2090 sheet has strength properties nearly equivalent to 7075-T6 sheet with improved exfoliation resistance. Refer to Section 3.1.3.4 for information on weldability of the alloy.

A material specification for 2090 aluminum alloy is shown in Table 3.2.5.0(a). Room-temperature mechanical and physical properties are shown in Table 3.2.5.0(b).

TABLE 3.2.5.0(a). *Material Specification for 2090 Aluminum Alloy.*

Specification	Form
AMS 4251	Sheet

The temper index is as follows:

Section	Temper
3.2.5.1	T83

3.2.5.1 *T83 Temper.*—Stress-strain and tangent-modulus curves are represented in Figures 3.2.5.1.6(a) and (b).

TABLE 3.2.5.0(b). *Design Mechanical and Physical Properties of 2090-T83 Sheet*

Specification	AMS 4251	
Form	Sheet	
Temper	T83	
Thickness, in.	0.040-0.125	0.126-0.249
Basis	S	S
Mechanical Properties:		
F_{tu}, ksi:		
L	77	75
45°	64	65
LT	73	73
F_{ty}, ksi:		
L	70	70
45°	56	57
LT	66	66
F_{cy}, ksi:		
L	67	63
45°	58	60
LT	71	71
F_{su}, ksi	37	37
F_{bru}[a], ksi:		
(e/D = 1.5)	100	100
(e/D = 2.0)	126	126
F_{bry}[a], ksi:		
(e/D = 1.5)	84	88
(e/D = 2.0)	98	104
e, percent:		
L	3	4
LT	5	5
E, 10^3 ksi:		
L & LT	11.5	
45°	11.0	
E_c, 10^3 ksi:		
L & LT	11.8	
45°	11.4	
G, 10^3 ksi	4.3	
μ	0.34	
Physical Properties:		
ω, lb/in.^{3}	0.093	
C, K, and α	...	

[a]Bearing values are "dry pin" values per Section 1.4.7.1.

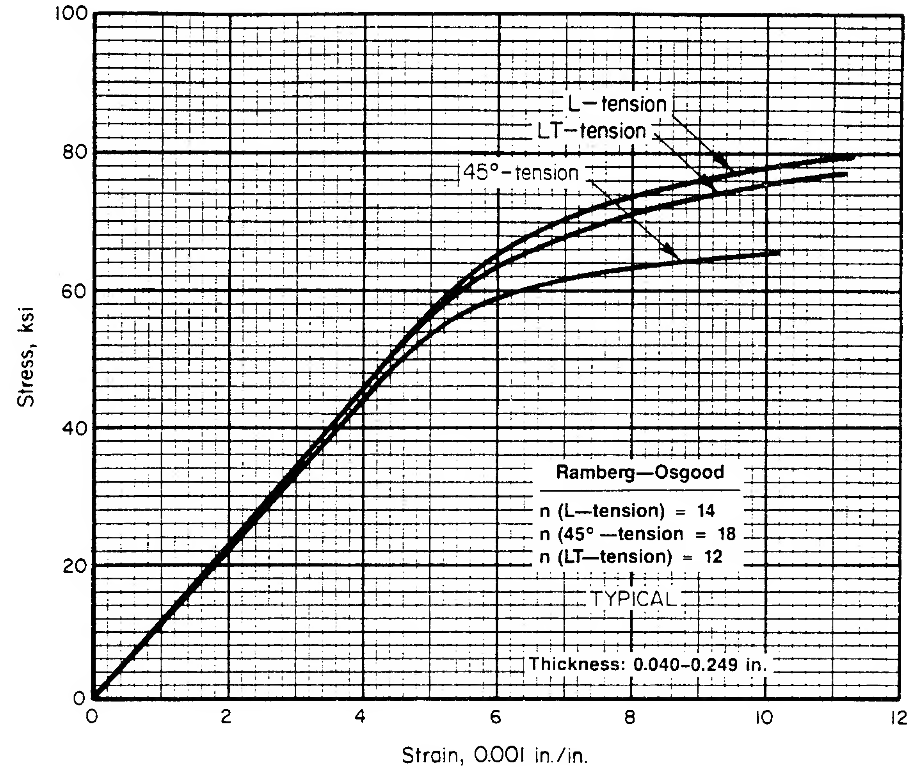

FIGURE 3.2.5.1.6(a). *Typical tensile stress-strain curves for 2090-T83 aluminum alloy sheet at room temperature.*

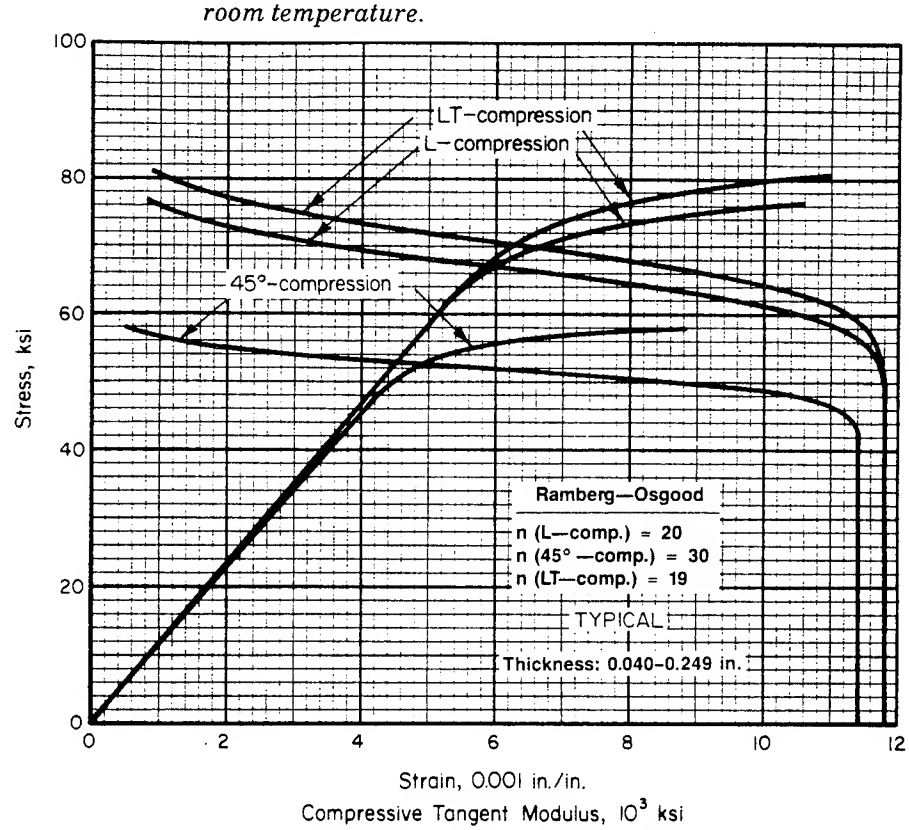

FIGURE 3.2.5.1.6(b). *Typical compressive stress-strain and compressive tangent-modulus curves for 2090-T83 aluminum alloy sheet at room temperature.*

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3.2.6 2124 ALLOY

3.2.6.0 *Comments and Properties.*—2124 is an Al-Cu alloy available in the form of plate in thicknesses of 1 through 6 inches. This alloy is a high purity version of alloy 2024. The higher purity in conjunction with special production processing provides higher elongation in the short-transverse direction and improved fracture toughness over that exhibited by conventionally produced 2024 alloy. The alloy is currently only produced in the T851 temper. The alloy like 2024 has excellent properties and creep resistance at elevated temperatures. The alloy in the T851 temper has good resistance to stress corrosion. Refer to Section 3.1.2.3.1 for information regarding resistance of the alloy to stress-corrosion cracking. Refer to Section 3.1.3.4 for comments regarding the weldability of the alloy. The physical properties are essentially the same as those for 2024-T851 plate.

Applicable material specification for 2124-T851 plate is presented in Table 3.2.6.0(a). Room-temperature mechanical properties are shown in Table 3.2.6.0(b).

TABLE 3.2.6.0(a). *Material Specification for 2124 Aluminum Alloy*

Specification	Form
AMS 4101	Plate
QQ-A-250/29	Plate

The temper index for 2124 is as follows:

Section	Temper
3.2.6.1	T851

3.2.6.1 *T851 Temper.*—Elevated temperature data are presented in Figures 3.2.6.1.1(a) and (b). Typical tensile stress-strain, compressive stress-strain, and compressive tangent-modulus curves are presented in Figures 3.2.6.1.6(a) and (b). Fatigue crack-propagation data for plate are presented in Figures 3.2.6.1.9(a) through (e).

TABLE 3.2.6.0(b). *Design Mechanical and Physical Properties of 2124 Aluminum Alloy Plate*

Specification	AMS 4101 and QQ-A-250/29										
Form	Plate										
Temper	T851										
Thickness, in.	1.000-1.500	1.501-2.000		2.001-3.000		3.001-4.000		4.001-5.000		5.001-6.000	
Basis	S	A	B	A	B	A	B	A	B	A	B
Mechanical Properties:											
F_{tu}, ksi:											
L	66	66	68	65	68	65	67	64	66	63	65
LT	66	66	68	65	68	65	67	64	66	63	65
ST	64[b]	64	66	63	64	62	63	61	62	58	59
F_{ty}, ksi:											
L	57	57	61	57	61	56	60	55	58	54	56
LT	57	57	61	57	61	56	60	55	58	54	56
ST	55[b]	55	59	55	59	54	57	53	55	51	53
F_{cy}, ksi:											
L	57	57	61	56	60	55	59	53	56	52	54
LT	57	57	61	57	61	56	60	55	58	54	56
ST	...	57	61	58	62	57	61	57	60	56	58
F_{su}, ksi:											
L	...	38	39	38	39	38	39	37	38	37	38
LT	...	38	39	38	39	38	39	37	38	37	38
ST	...	36	37	36	37	36	37	35	36	35	36
F_{bru}[a], ksi:											
(e/D = 1.5)	...	97	100	96	100	96	99	94	97	93	96
(e/D = 2.0)	...	126	130	125	130	125	128	123	126	121	125
F_{bry}[a], ksi:											
(e/D = 1.5)	...	79	84	80	85	80	85	79	84	79	82
(e/D = 2.0)	...	91	98	92	99	92	99	92	97	91	95
e, percent (S-basis):											
L	6	6	...	6	...	5	...	5	...	5	...
LT	5	5	...	4	...	4	...	4	...	4	...
ST	1.5[b]	1.5	...	1.5	...	1.5	...	1.5	...	1.5	...
E, 10^3 ksi	10.4										
E_c, 10^3 ksi	10.9										
G, 10^3 ksi	4.0										
μ	0.33										
Physical Properties:											
ω, lb/in.^{3}	0.100										
C, Btu/(lb)(F)	0.21 (at 212 F)										
K, Btu/[(hr)(ft^3)(F)/ft]	87 (at 77 F)										
α, 10^{-6} in./in./F	12.6 (68 F to 212 F)										

[a]Bearing values are "dry pin" values per Section 1.4.7.1. See Table 3.1.2.1.1.
[b]Applicable to 1.500-inch thickness only.

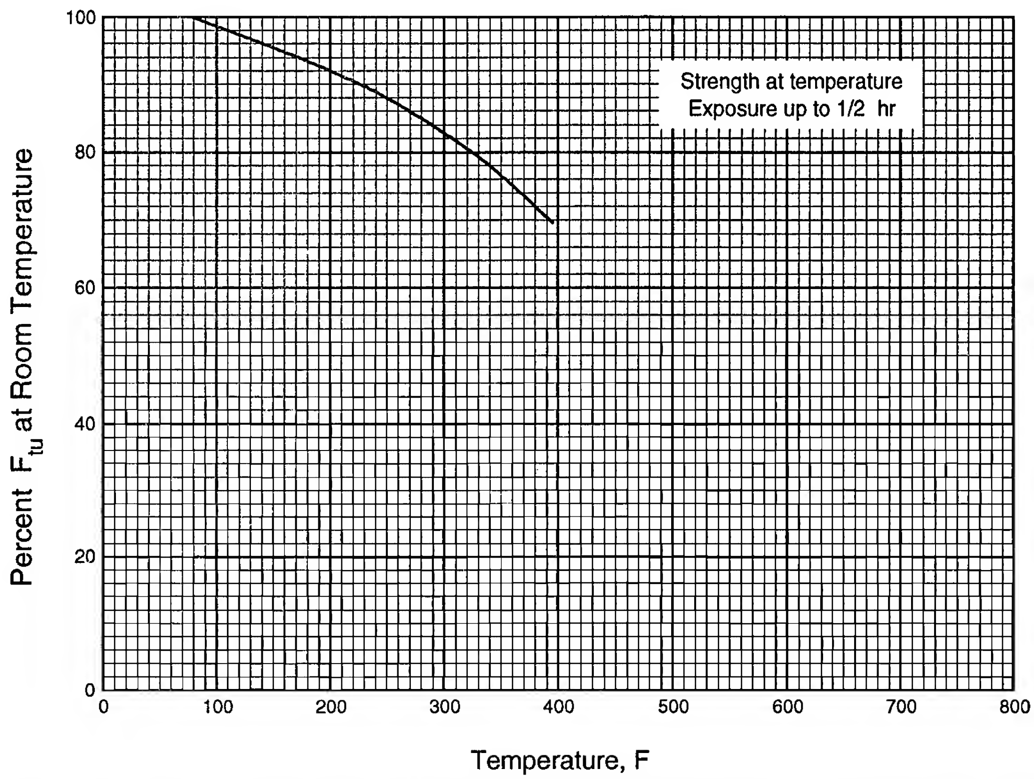

FIGURE 3.2.6.1.1(a). *Effect of temperature on the tensile ultimate strength (F_{tu}) of 2124-T851 aluminum alloy plate.*

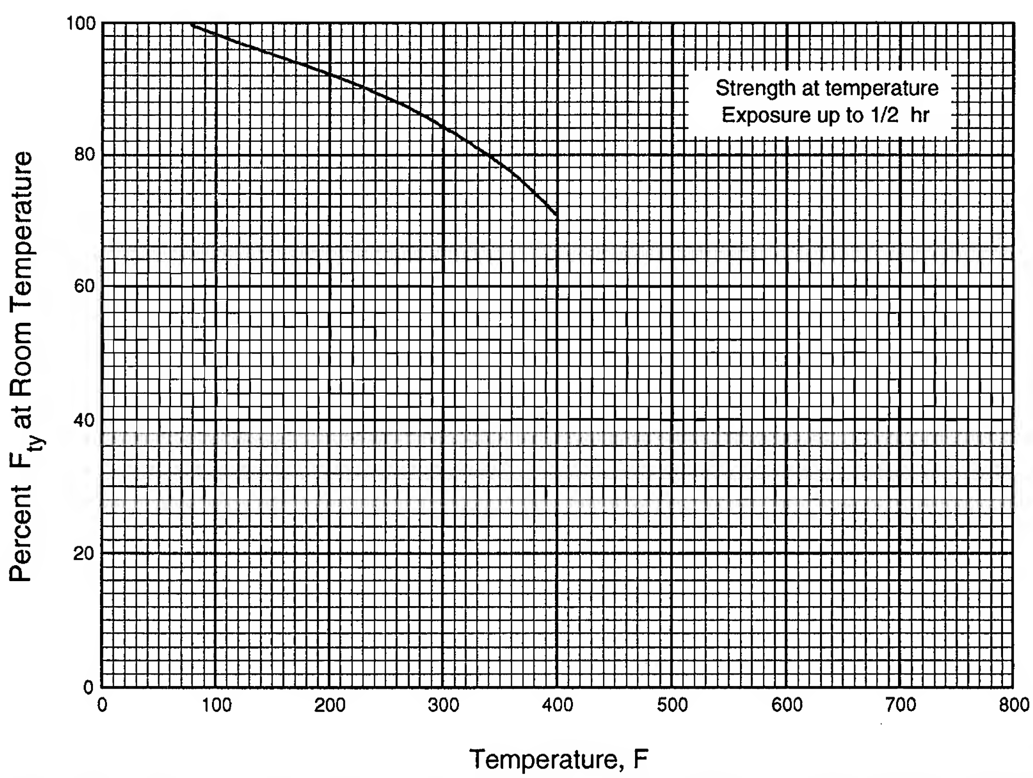

FIGURE 3.2.6.1.1(b). *Effect of temperature on the tensile yield strength (F_{ty}) of 2124-T851 aluminum alloy plate.*

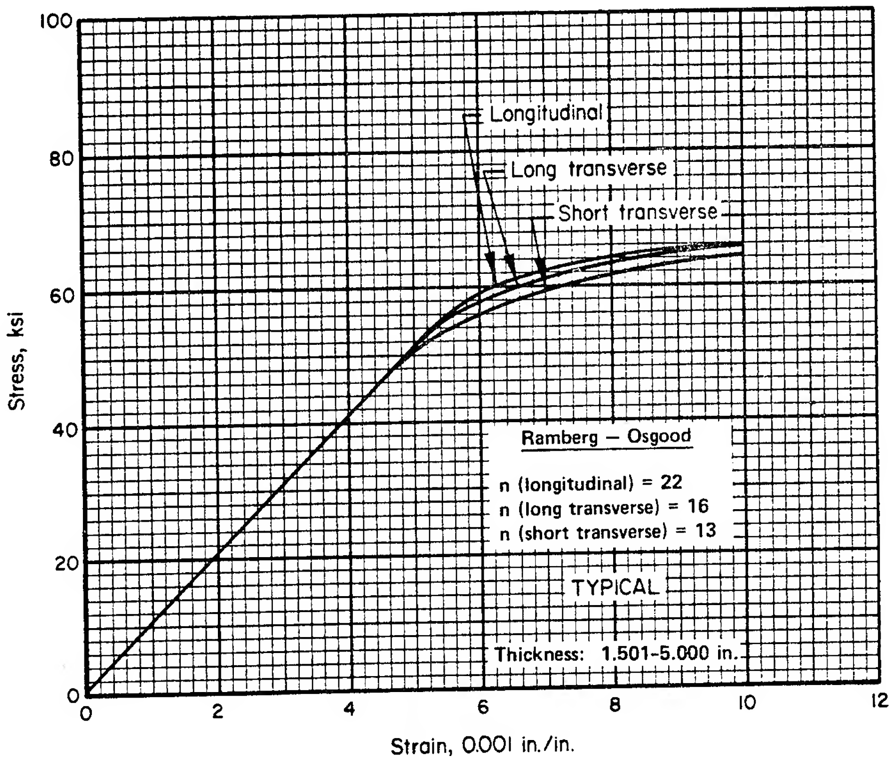

FIGURE 3.2.6.1.6(a). *Typical tensile stress-strain curves for 2124-T851 aluminum alloy plate at room temperature.*

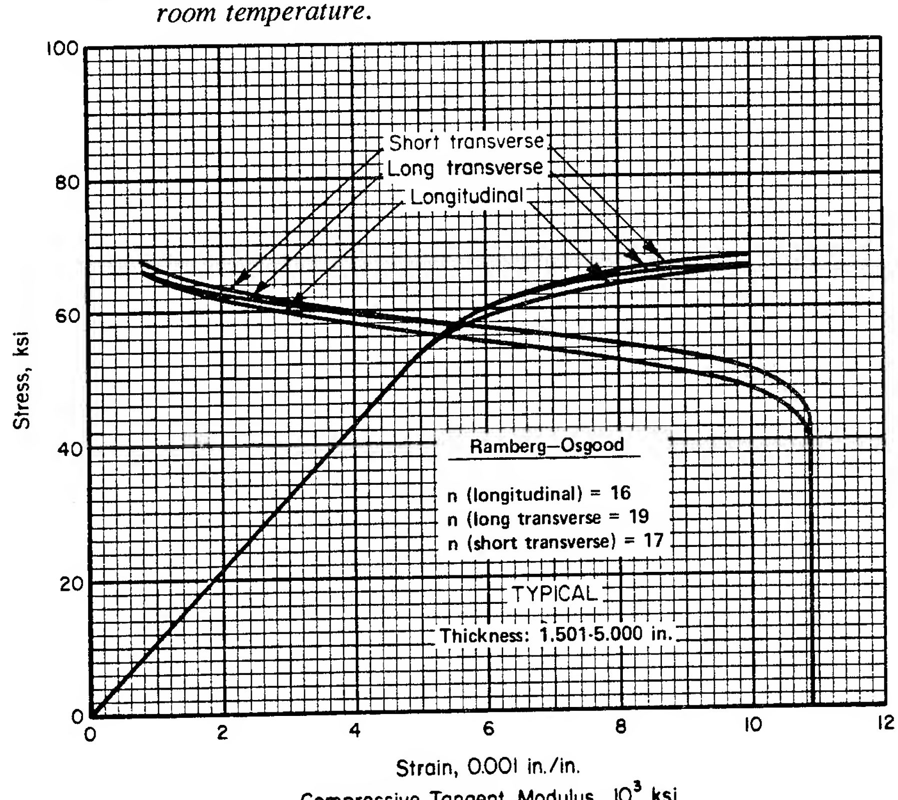

FIGURE 3.2.6.1.6(b). *Typical compressive stress-strain and compressive tangent-modulus curves for 2124-T851 aluminum alloy plate at room temperature.*

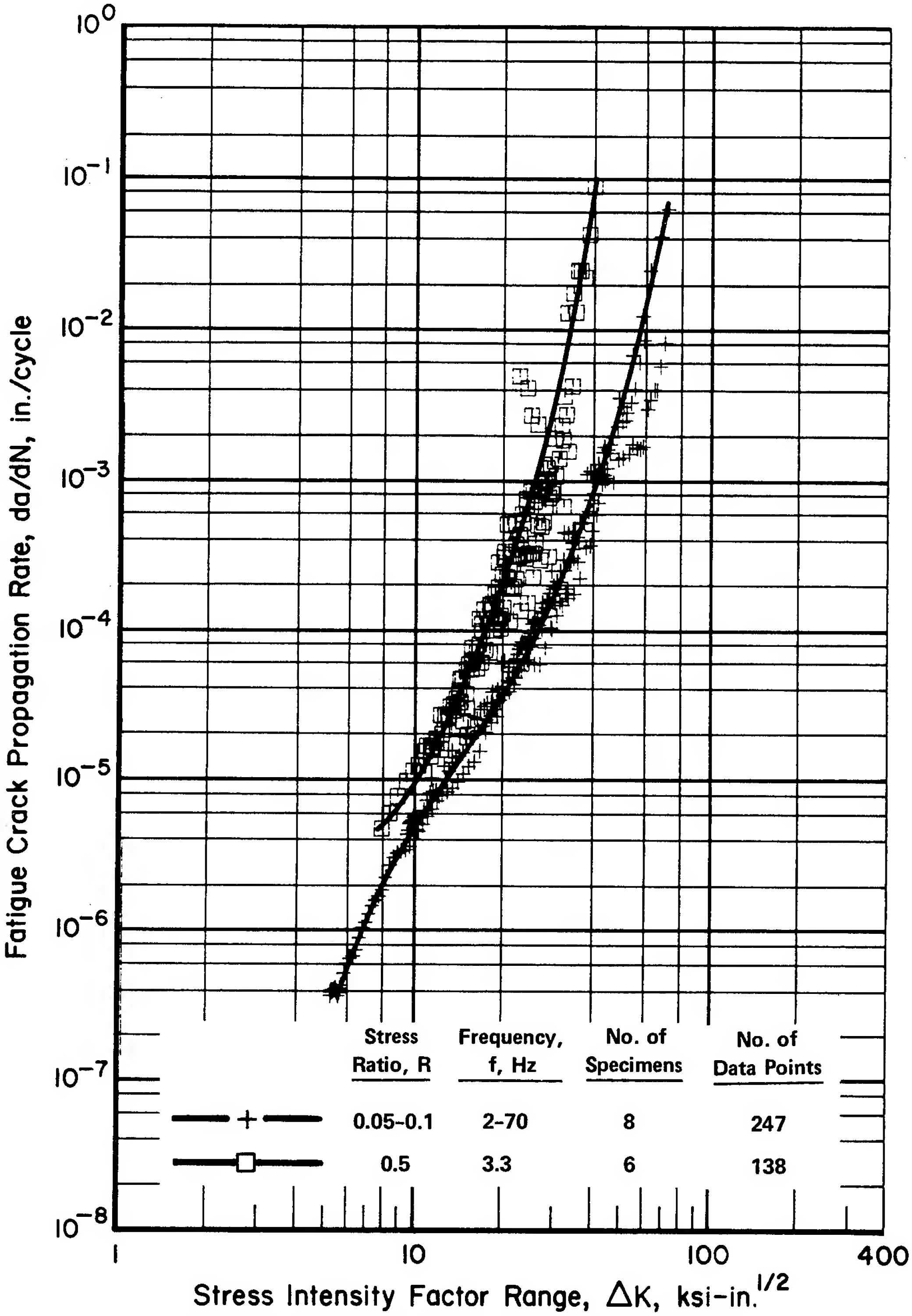

FIGURE 3.2.6.1.9(a). *Fatigue-crack-propagation data for 2.0 to 5.5 inch thick, 2124-T851 aluminum alloy plate. [References 3.2.6.1.9(a), 3.2.6.1.9(c), and 3.2.6.1.9(d)]*

Specimen Thickness:	*0.25-0.45 and 0.15 inch*	*Environment:*	*95% R.H.*
Specimen Width:	*11.75 and 3.0 inches*	*Temperature:*	*RT*
Specimen Type:	*CC and CT*	*Orientation:*	*L-T*

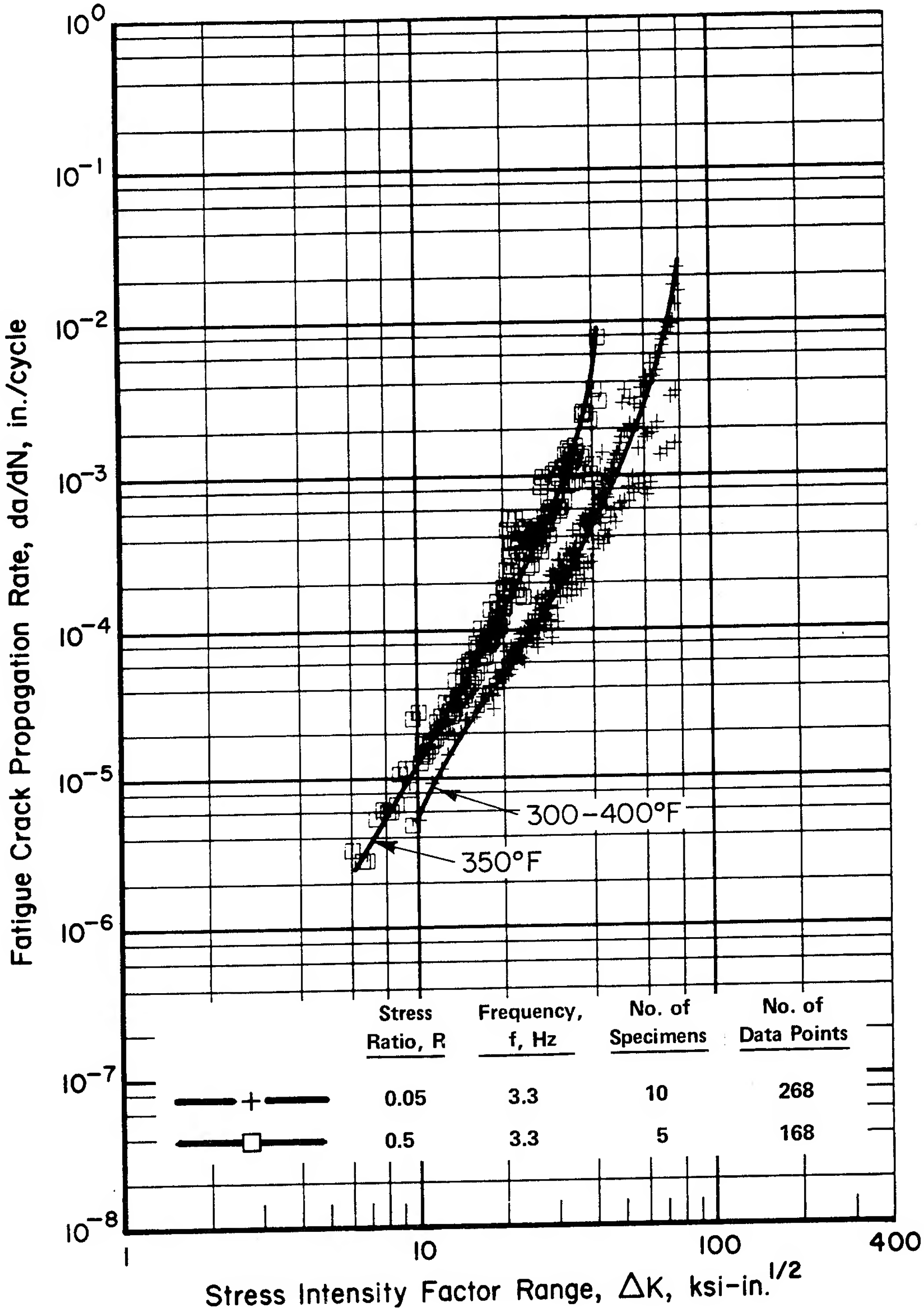

FIGURE 3.2.6.1.9(b). *Fatigue-crack-propagation data for 2.0-inch thick, 2124-T851 aluminum alloy plate. [Reference 3.2.6.1.9(a)]*

Specimen Thickness:	*0.25-0.45 inch*	*Environment:*	*Lab air*
Specimen Width:	*11.75 inches*	*Temperature:*	*300-400°F*
Specimen Type:	*CC*	*Orientation:*	*L-T*

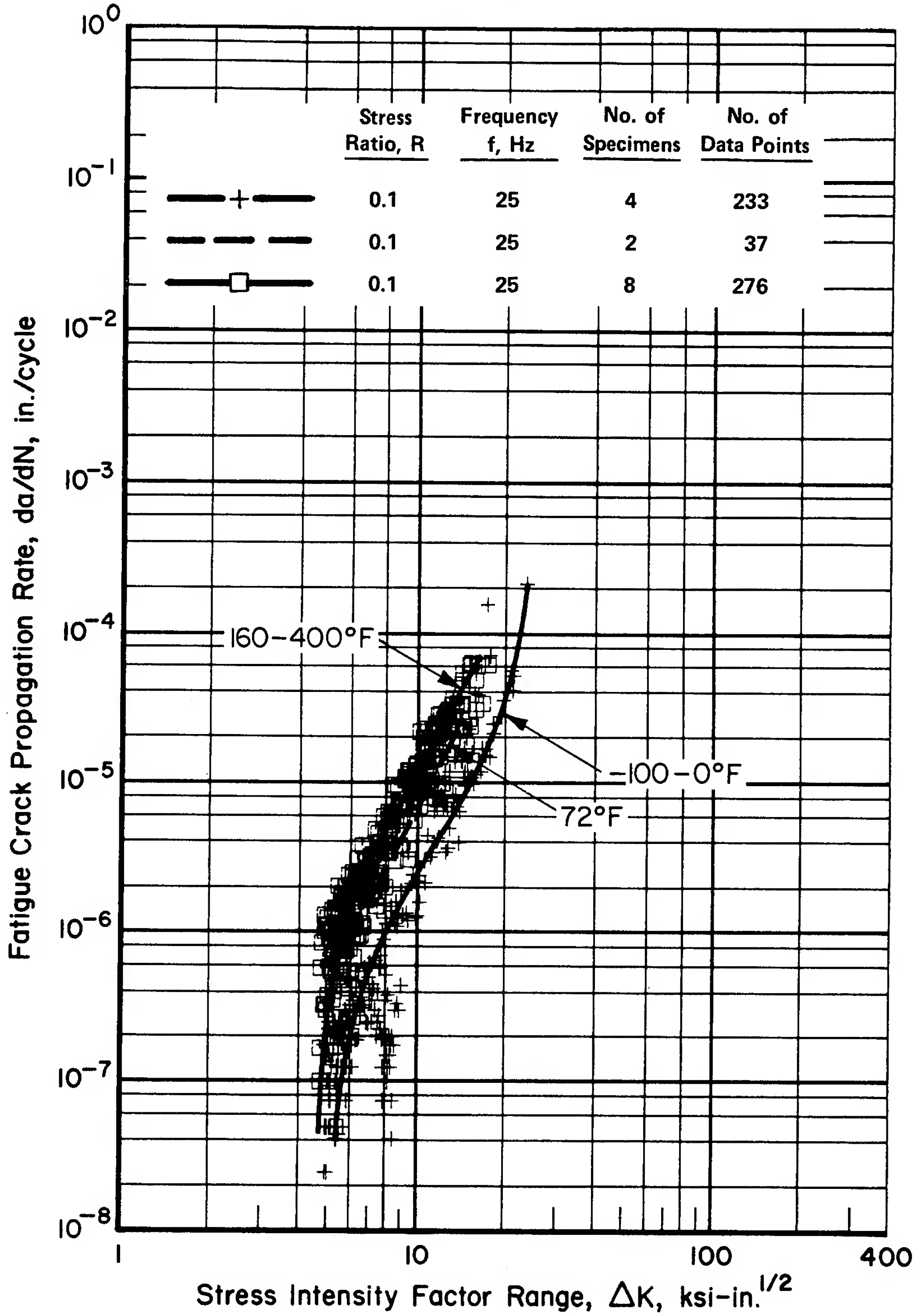

FIGURE 3.2.6.1.9(c). *Fatigue-crack-propagation data for 2.5-inch thick, 2124-T851 aluminum alloy plate. [Reference 3.2.6.1.9(b)]*

Specimen Thickness:	*0.75 inch*	*Environment:*	*Lab air*
Specimen Width:	*1.75 inches*	*Temperature:*	*-100 through 400°F*
Specimen Type:	*CT*	*Orientation:*	*L-T*

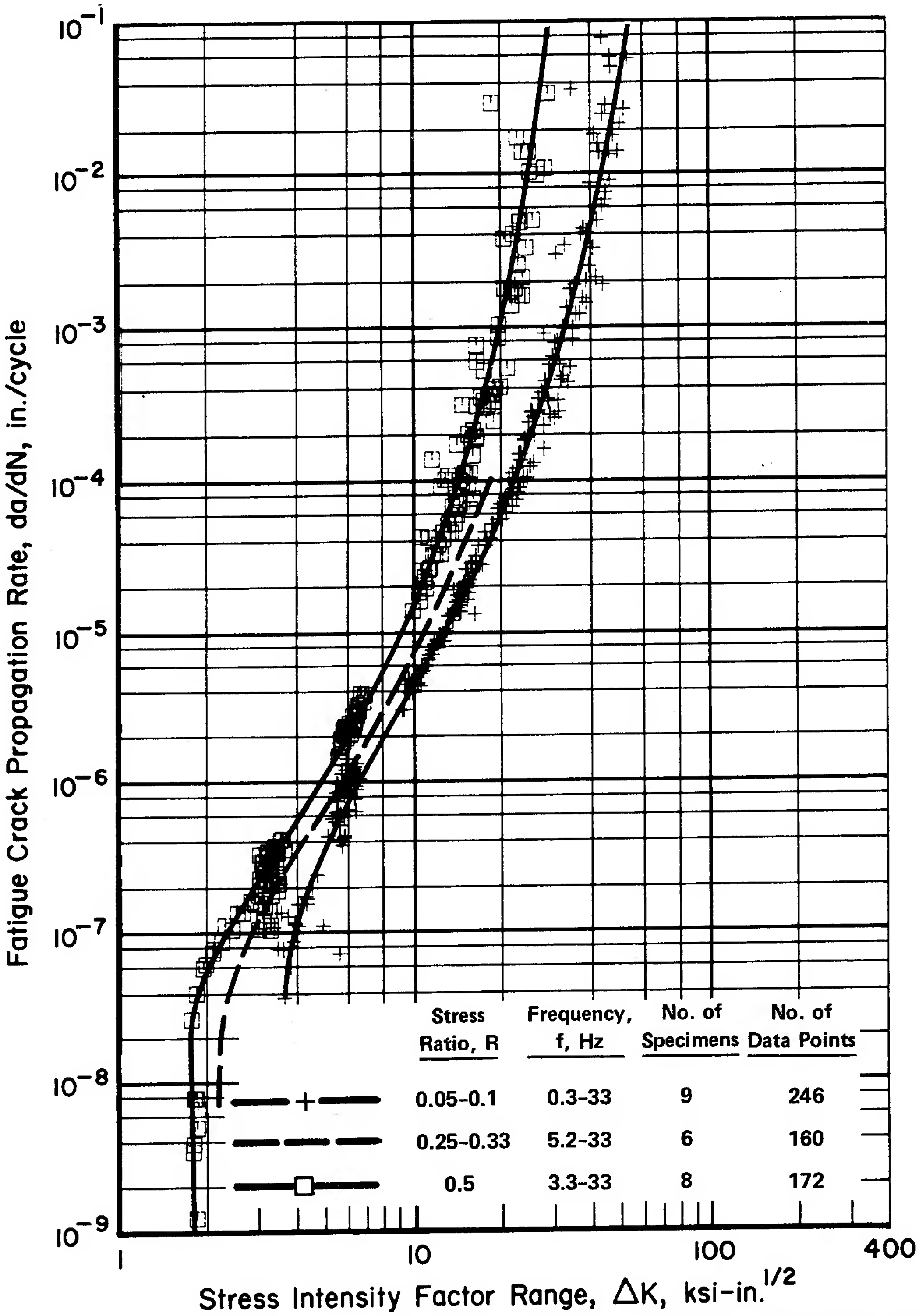

FIGURE 3.2.6.1.9(d). *Fatigue-crack-propagation data for 2.0 to 5.5 inch thick, 2124-T851 aluminum alloy plate. [References 3.2.6.1.9(a), 3.2.6.1.9(d), and 3.7.4.2.9(c)]*

Specimen Thickness:	*0.25-0.75 inch*	*Environment:*	*90-95% R.H.*
Specimen Width:	*4.0-11.75 inches*	*Temperature:*	*RT*
Specimen Type:	*CC*	*Orientation:*	*T-L*

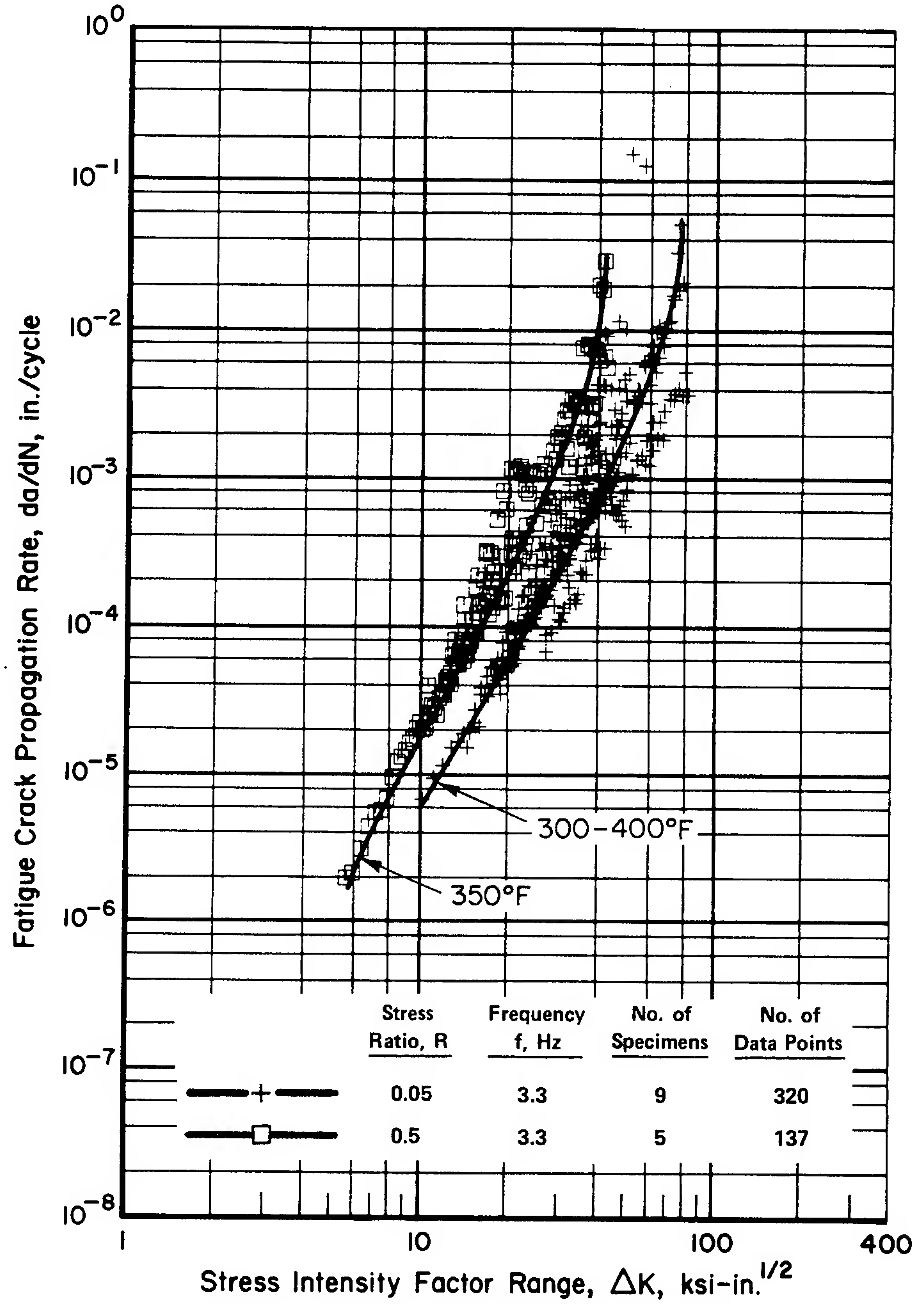

FIGURE 3.2.6.1.9(e). *Fatigue-crack-propagation data for 2.0-inch thick, 2124-T851 aluminum alloy plate. [Reference 3.2.6.1.9(a)]*

Specimen Thickness:	*0.25-0.45 inch*	*Environment:*	*Lab air*
Width:	*11.75 inches*	*Temperature:*	*300-400°F*
Type:	*CC*	*Orientation:*	*T-L*

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3.2.7 2219 ALLOY

3.2.7.0 *Comments and Properties.*—2219 is an Al-Cu alloy available in a wide variety of product forms. Refer to Section 3.1.2.3 for comments regarding the resistance of the alloy to stress-corrosion cracking, and to Section 3.1.3.4 for comments regarding the weldability of the alloy. It has been used in critical cryogenic applications as well as those in which high strength and creep resistance at relatively high temperatures (400 to 600 F) are required.

Material specifications for 2219 are presented in Table 3.2.7.0(a). Room-temperature mechanical and physical properties are shown in Tables 3.2.7.0(b_1) through (d). The effect of temperature on the physical properties is shown in Figure 3.2.7.0.

TABLE 3.2.7.0(a). *Material Specifications for 2219 Aluminum Alloy*

Specification	Form
AMS 4031	Sheet and plate
QQ-A-250/30	Sheet and plate
AMS 4162	Extrusion
AMS 4163	Extrusion
AMS 4144	Hand forging

The temper index for 2219 is as follows:

Section	Temper
3.2.7.1	T62
3.2.7.2	T81, T851, T8510, and T8511
3.2.7.3	T852
3.2.7.4	T87

3.2.7.1 *T62 Temper.*—Elevated temperature data for this temper are presented in Figures 3.2.7.1.1(a) and (b). Typical room-temperature tensile and compressive stress-strain, compressive tangent-modulus, and full-range tensile stress-strain curves for 2219 aluminum alloy sheet and plate for this temper are shown in Figures 3.2.7.1.6(a) and (b).

3.2.7.2 *T81 and T851X Tempers.*—Elevated temperature data for these tempers are presented in Figures 3.2.7.2.1(a) and (b). Typical room-temperature tensile and compressive stress-strain, compressive tangent-modulus, and full-range tensile stress-strain curves for 2219 aluminum alloy for this condition are shown in Figures 3.2.7.2.6(a) and (b). Notched fatigue data for plate are presented in Figures 3.2.7.2.8(a) through (d).

3.2.7.3 *T852 Temper.*—Typical room-temperature tensile and compressive stress-strain, compressive tangent-modulus, and full-range tensile stress-strain curves for 2219 aluminum alloy for this temper are shown in Figures 3.2.7.3.6(a) through (e).

3.2.7.4 *T87 Temper.*—Elevated temperature data for this temper are presented in Figures 3.2.7.4.1(a) and (b). Typical room-temperature tensile and compressive stress-strain, compressive tangent-modulus, and full-range tensile stress-strain curves for 2219 aluminum alloy sheet and plate for this temper are shown in Figures 3.2.7.4.6(a) through (c).

TABLE 3.2.7.0(b$_1$). *Design Mechanical and Physical Properties of 2219 Aluminum Alloy Sheet and Plate*

Specification	AMS 4031 & QQ-A-250/30		QQ-A-250/30													
Form	Sheet and plate															
Temper	T62[a]		T81		T851											
Thickness, in.	0.020-2.000		0.020-0.249		0.250-1.000		1.001-2.000		2.001-3.000		3.001-4.000		4.001-5.000		5.001-6.000	
Basis	A	B	A	B	A	B	A	B	A	B	A	B	A	B	A	B
Mechanical Properties:																
F_{tu}, ksi:																
L	54	55	61	62	61	62	61	62	...	...	...	...	...	...	...	...
LT	54	55	62	63	62	63	62	63	62	63	60	61	59	60	57	58
F_{ty}, ksi:																
L	36	37	47	48	47	48	47	48	...	...	...	...	...	...	...	...
LT	36	37	46	47	46	47	46	47	45	46	44	45	43	44	42	43
F_{cy}, ksi:																
L	37	39	47	48	47	48	47	48	...	...	...	...	...	...	...	...
LT	37	38	48	49	48	49	48	49	...	...	...	...	...	...	...	...
F_{su}, ksi	31	32	35	35	36	36	36	36	...	...	...	...	...	...	...	...
F_{bru}[b], ksi:																
(e/D = 1.5)	84	85	95	96	95	96	95	96	...	...	...	...	...	...	...	...
(e/D = 2.0)	107	109	121	123	121	123	121	123	...	...	...	...	...	...	...	...
F_{bry}[b], ksi:																
(e/D = 1.5)	62	64	76	78	76	78	76	78	...	...	...	...	...	...	...	...
(e/D = 2.0)	79	81	92	94	94	94	92	94	...	...	...	...	...	...	...	...
e, percent (S-basis):																
LT	c	...	c	...	8	...	7	...	6	...	5	...	5	...	4	...
E, 10^3 ksi	10.5															
E_c, 10^3 ksi	10.8															
G, 10^3 ksi	4.0															
μ	0.33															
Physical Properties:																
ω, lb/in.^{3}	0.103															
C, K, and α	See Figure 3.2.7.0															

[a] Design allowables were based upon data obtained from testing samples of material, supplied in O and F temper, which were heat treated to demonstrate response to heat treatment by suppliers. Properties obtained by user may be lower than those listed if the material has been formed or otherwise cold or hot worked, particularly in the annealed temper, prior to solution heat treatment.
[b] Bearing values are "dry pin" values per Section 1.4.7.1. See Table 3.1.2.1.1.
[c] T62 and T81: 0.020-0.039 in., 6 percent, 0.040-0.249 in., 7 percent; T62: 0.250-1.000 in., 8 percent, 1.001-2.000 in., 7 percent.

TABLE 3.2.7.0(b_2). *Design Mechanical and Physical Properties of 2219 Alluminum Alloy Sheet — Continued*

Specification	QQ-A-250\30			
Form	Sheet			
Condition	T87			
Thickness, in.	0.020-0.039		0.040-0.249	
Basis	A	B	A	B
Mechanical Properties:				
F_{tu}, ksi:				
L	63	64	63	64
LT	64	65	64	65
F_{ty}, ksi:				
L	51	52	51	52
LT	52	53	52	53
F_{cy}, ksi:				
L	52	53	52	53
LT	55	56	55	56
F_{su}, ksi	36	37	36	37
F_{bru}[a], ksi:				
(e/D = 1.5)	99	100	99	100
(e/D = 2.0)	126	128	126	128
F_{bry}[a], ksi:				
(e/D = 1.5)	83	85	83	85
(e/D = 2.0)	96	98	96	98
e, percent (S-basis):				
LT	5	...	6	...
E, 10^3 ksi	10.5			
E_c, 10^3, ksi	10.8			
G, 10^3, ksi	4.0			
μ	0.33			
Physical Properties:				
ω, lb/in.^{3}	0.103			
C, K, and α	See Figure 3.2.7.0			

[a]See Table 3.1.2.1.1. Bearing values are "dry pin" values per Section 1.4.7.1.

TABLE 3.2.7.0(b$_3$). *Design Mechanical and Physical Properties of 2219 Alluminum Alloy Plate — Continued*

Specification	QQ-A-250\30											
Form	Plate											
Condition	T87											
Thickness, in.	0.250-1.000		1.001-1.500		1.501-2.000		2.001-3.000		3.001-4.000		4.001-5.000	
Basis	A	B	A	B	A	B	A	B	A	B	A	B
Mechanical Properties:												
F_{tu}, ksi:												
L	63	64	63	64	63	64	63	64	61	62	...	...
LT	64	65	64	65	64	65	64	65	62	63	61	62
ST	...	...	...	...	59	60	56	57	52	53	...	...
F_{ty}, ksi:												
L	50	51	50	51	50	51	50	51	49	50	...	...
LT	51	52	51	52	51	52	51	52	51	51	49	50
ST	...	...	...	...	51	52	50	51	48	49	...	...
F_{cy}, ksi:												
L	51	52	51	52	51	52	...	...	...	...	...	...
LT	53	54	52	53	52	53	...	...	...	...	...	...
F_{su}, ksi	37	38	37	38	37	38	...	...	...	...	...	...
F_{bru}[a], ksi:												
(e/D = 1.5)	99	100	99	100	99	100	...	...	...	...	...	...
(e/D = 2.0)	126	128	126	128	126	128	...	...	...	...	...	...
F_{bry}[a], ksi:												
(e/D = 1.5)	82	83	82	83	82	83	...	...	...	...	...	...
(e/D = 2.0)	94	96	94	96	94	96	...	...	...	...	...	...
e, percent (S-basis):												
LT	7	...	6	...	6	...	6	...	4	...	3	...
E, 10^3 ksi	10.5											
E_c, 10^3, ksi	10.8											
G, 10^3, ksi	4.0											
μ	0.33											
Physical Properties:												
ω, lb/in.^{3}	0.103											
C, K, and α	See Figure 3.2.7.0											

[a]See Table 3.1.2.1.1. Bearing values are "dry pin" values per Section 1.4.7.1.

TABLE 3.2.7.0(c). *Design Mechanical and Physical Properties of 2219 Aluminum Alloy Hand Forging*

Specification	AMS 4144							
Form	Hand forging							
Temper	T852							
Thickness, in.	<2.000	2.000-4.000	4.001-6.000	6.001-8.000	8.001-10.000	10.001-12.000	12.001-14.000	14.001-17.000
Basis	S	S	S	S	S	S	S	S
Mechanical Properties:								
F_{tu}, ksi:								
L								
LT	62	62	58	57	56	54	53	51
ST	62	62	56	55	54	53	52	50
F_{ty}, ksi:	...	60	56	55	54	53	52	50
L								
LT	50	50	44	43	42	41	40	39
ST	49	49	42	41	41	40	40	39
F_{cy}, ksi:	...	46	41	40	39	39	38	37
L								
LT	...	46	40	39	...	...	...	...
ST	...	47	40	39	...	...	...	...
F_{su}, ksi:	...	47	41	40	...	...	...	...
L								
LT	...	37	35	35	...	...	...	...
ST	...	36	34	35	...	...	...	...
F_{bru}[a], ksi:	...	32	32	33	...	...	...	...
(e/D = 1.5)								
(e/D = 2.0)	...	...	...	80	...	...	...	...
F_{bry}[a], ksi:	...	104	100	102	...	...	...	...
(e/D = 1.5)								
(e/D = 2.0)	...	76	65	64	...	...	...	...
e, percent:	...	89	76	75	...	...	...	...
L								
LT	6	6	6	6	6	6	6	6
ST	4	4	4	4	3	3	3	3
	...	3	3	3	3	2	2	2
E, 10^3 ksi	10.2							
E_c, 10^3 ksi	10.4							
G, 10^3 ksi	3.9							
μ	0.33							
Physical Properties:	0.33							
ω, lb/in.^{3}	0.103							
C, K, and α	See Figure 3.2.7.0							

[a]Bearing values are "dry pin" values per Section 1.4.7.1.

TABLE 3.2.7.0(d). *Design Mechanical and Physical Properties of 2219 Aluminum Alloy Extruded Shapes*

Specification	AMS 4162 and AMS 4163[a]	
Form	Extruded shapes	
Temper	T8511	
Cross-sectional area, in.^{2}	≤25	
Thickness or diameter, in.	≤0.499	0.500-2.999
Basis	S	S
Mechanical Properties:		
F_{tu}, ksi:		
L	58	58
LT[b]	56	56
F_{ty}, ksi:		
L	42	42
LT[b]	39	39
F_{cy}, ksi:		
L	43	42
LT	43	41
F_{su}, ksi	33	33
F_{bru}[c], ksi:		
(e/D = 1.5)	87	81
(e/D = 2.0)	113	107
F_{bry}[c], ksi:		
(e/D = 1.5)	69	67
(e/D = 2.0)	84	82
e, percent:		
L	6	6
LT[b]	4	4
E, 10^3 ksi	10.5	
E_c, 10^3 ksi	10.8	
G, 10^3 ksi	4.0	
μ	0.33	
Physical Properties:		
ω, lb/in.^{3}	0.103	
C, K, and α	See Figure 3.2.7.0	

[a]Design allowables for extrusions procured to AMS 4163 were based upon data obtained from testing samples of material, supplied in T3511 temper, which were precipitation heat treated by suppliers to demonstrate response to aging treatment.
[b]Applicable providing LT dimension is ≥2.500 inches.
[c]Bearing values are "dry pin" values per Section 1.4.7.1.

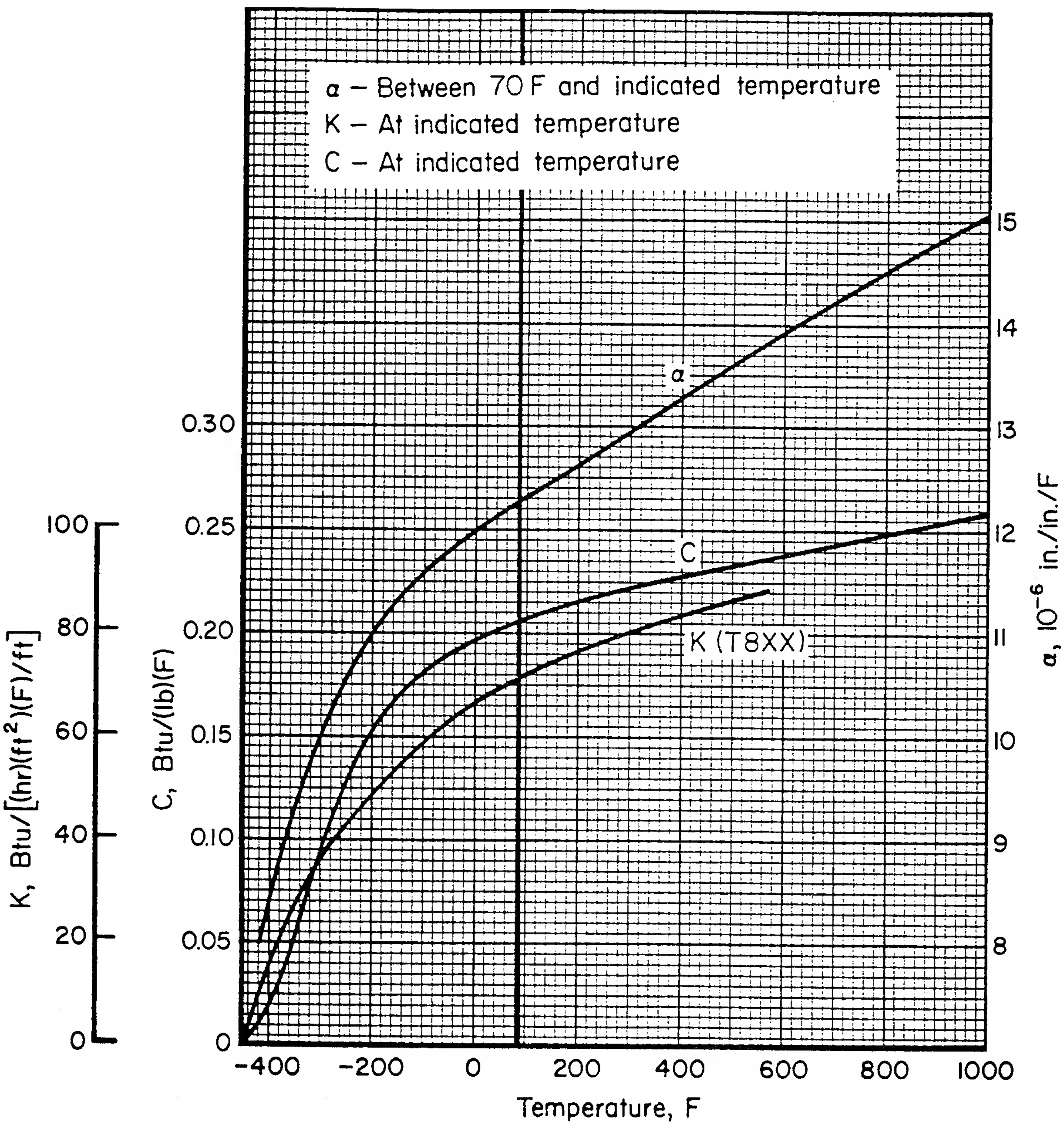

FIGURE 3.2.7.0. *Effect of temperature on the physical properties of 2219 aluminum alloy.*

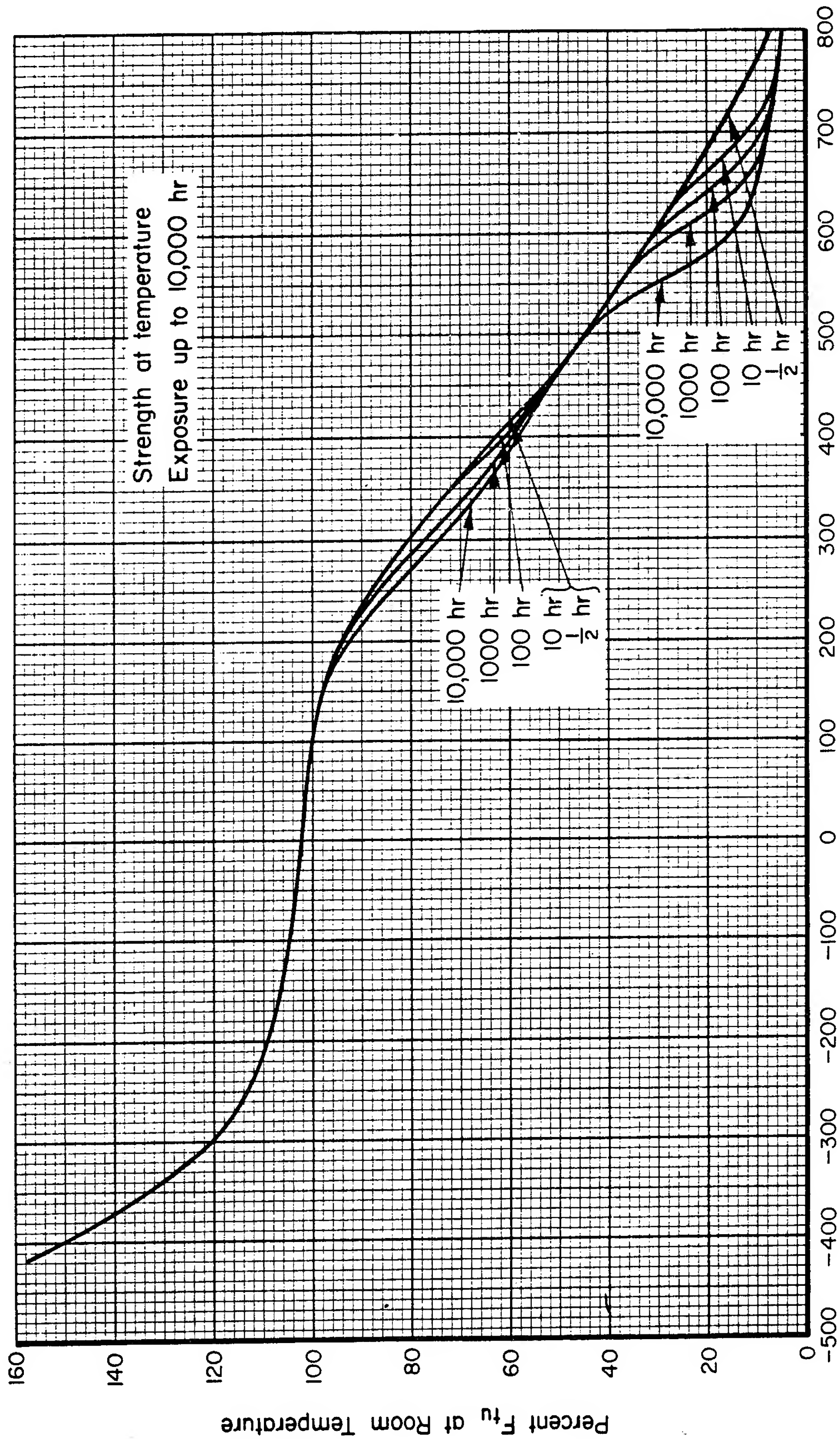

FIGURE 3.2.7.1.1(a). *Effect of temperature on the tensile ultimate strength (F_{tu}) of 2219-T62 aluminum alloy sheet, 0.040-0.249, and plate, 0.250-1.000 in. thick.*

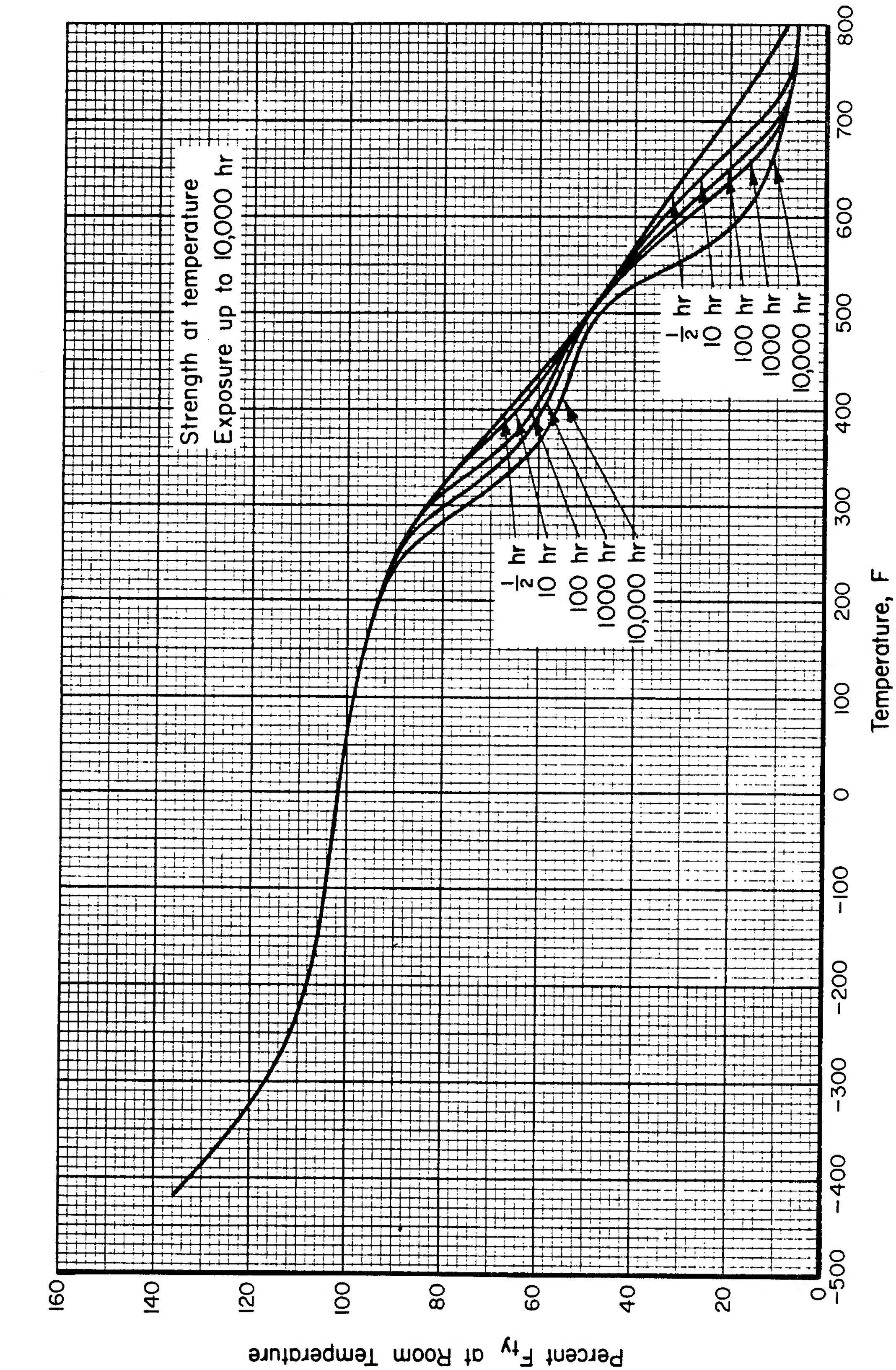

FIGURE 3.2.7.1.1(b). *Effect of temperature on the tensile yield strength (F_{ty}) of 2219-T62 aluminum alloy sheet 0.040-0.249 and plate, 0.250-1.000 in. thick.*

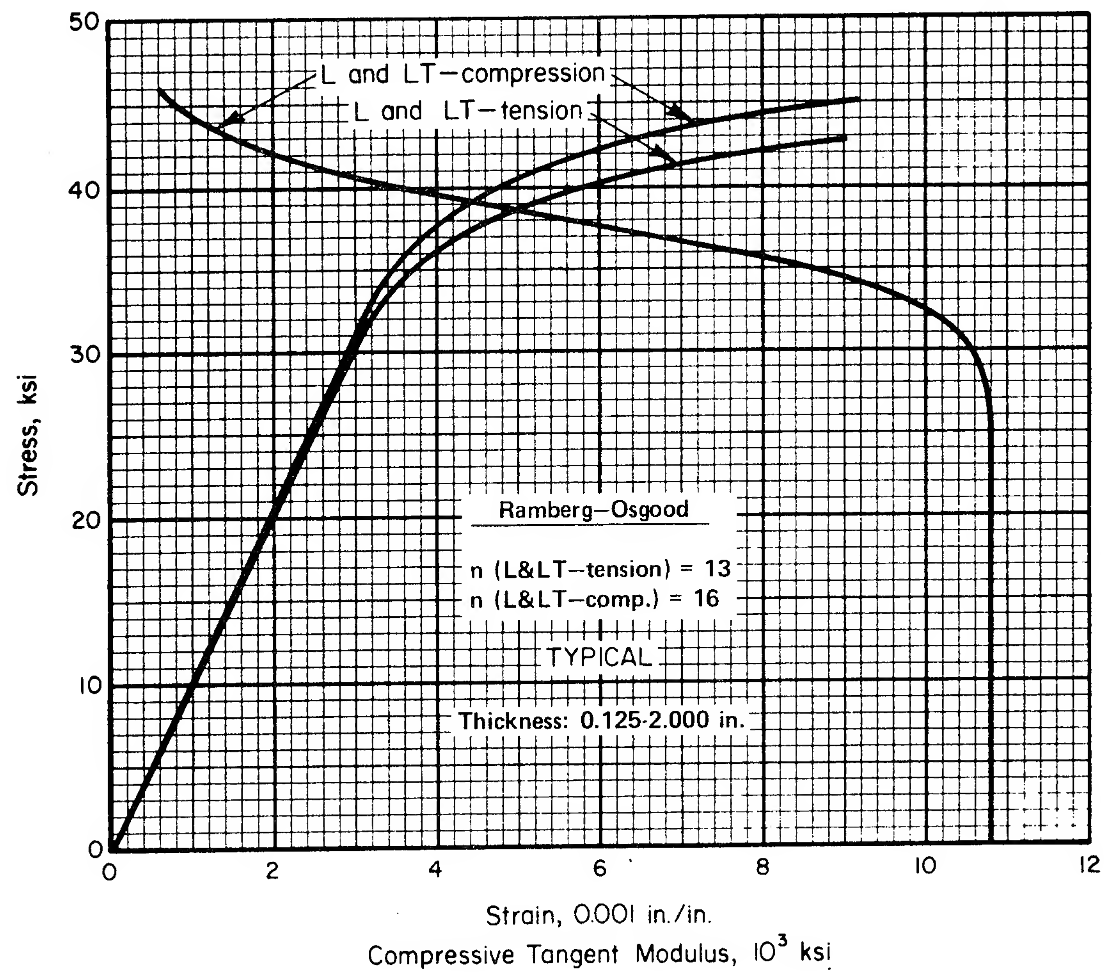

FIGURE 3.2.7.1.6(a). *Typical tensile and compressive stress-strain and compressive tangent-modulus curves for 2219-T62 aluminum alloy sheet and plate at room temperature.*

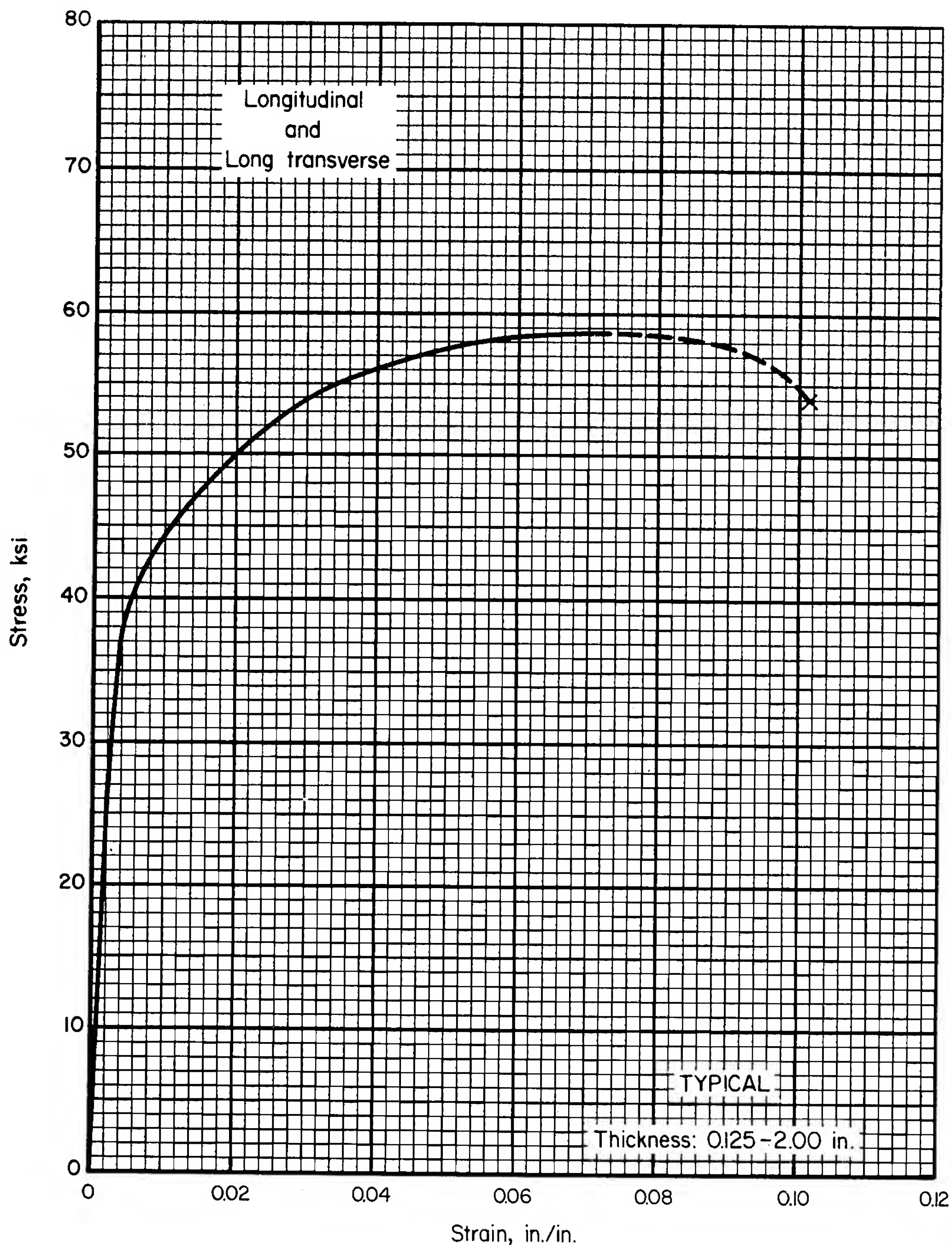

FIGURE 3.2.7.1.6(b). *Typical tensile stress-strain (full range) curve for 2219-T62 aluminum alloy sheet and plate at room temperature.*

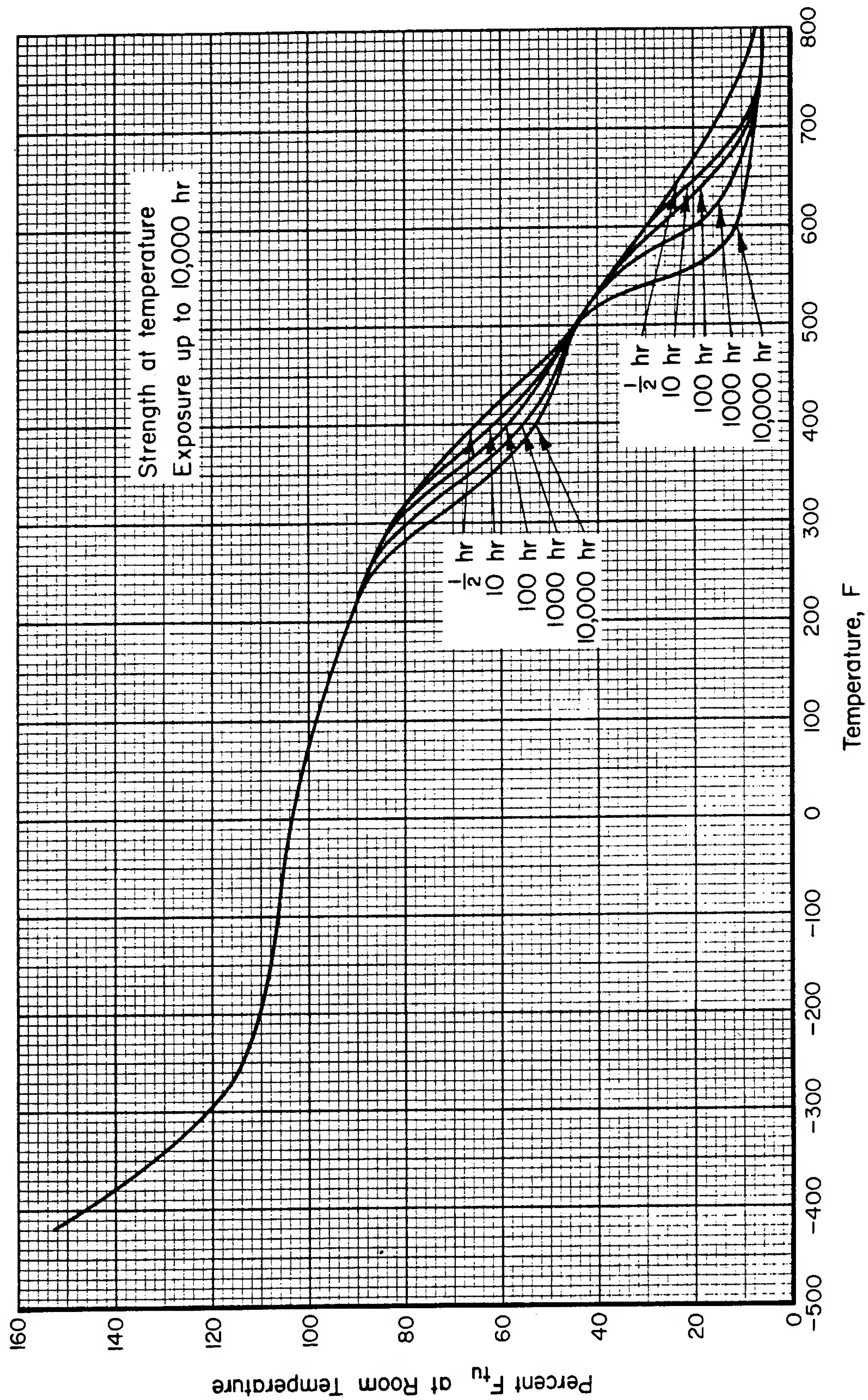

FIGURE 3.2.7.2.1(a). *Effect of temperature on the tensile ultimate strength (F_{tu}) of 2219-T81 aluminum alloy sheet and 2219-T851 aluminum alloy plate.*

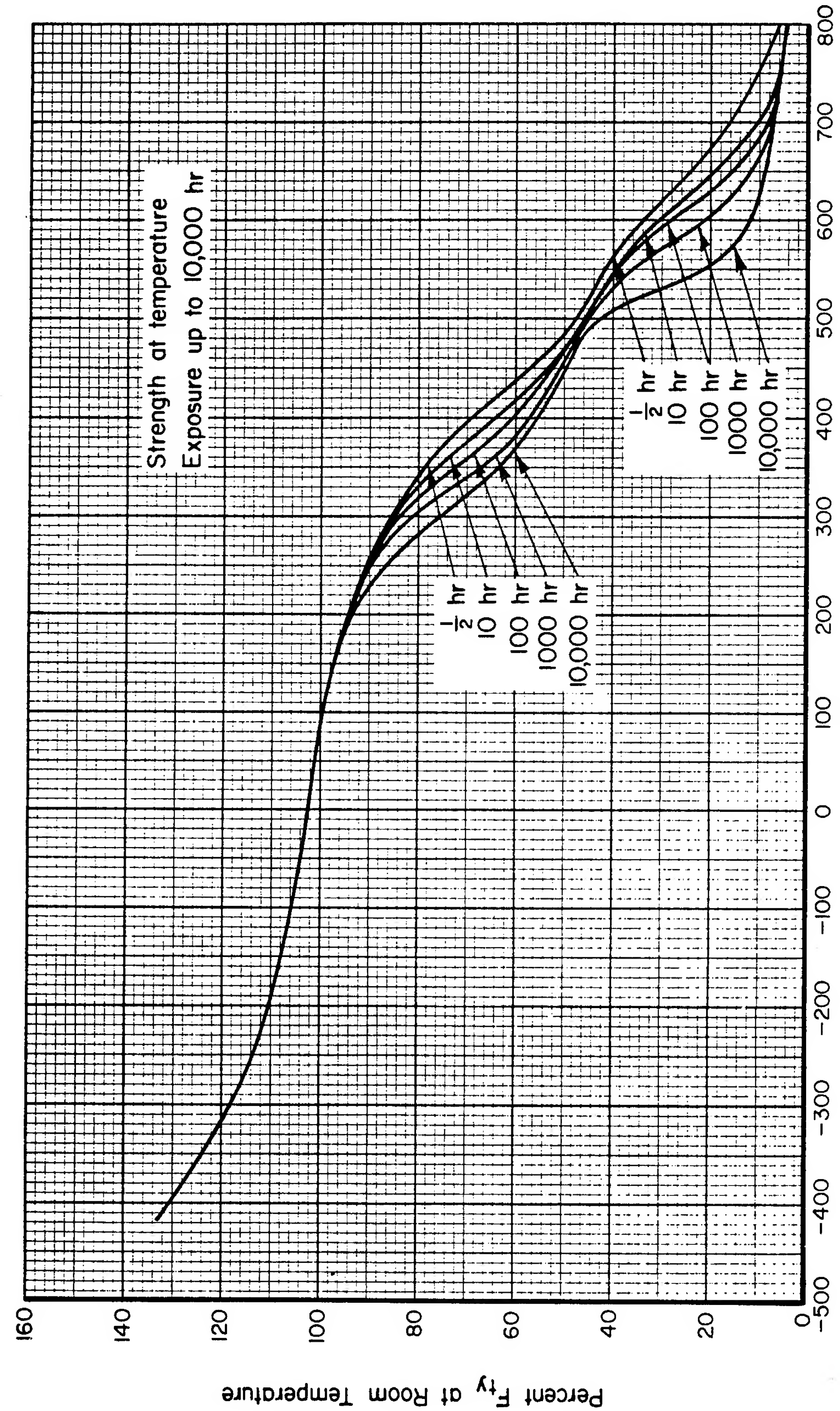

FIGURE 3.2.7.2.1(b). *Effect of temperature on the tensile yield strength (F_{ty}) of 2219-T81 aluminum alloy sheet and 2219-T851 aluminum alloy plate.*

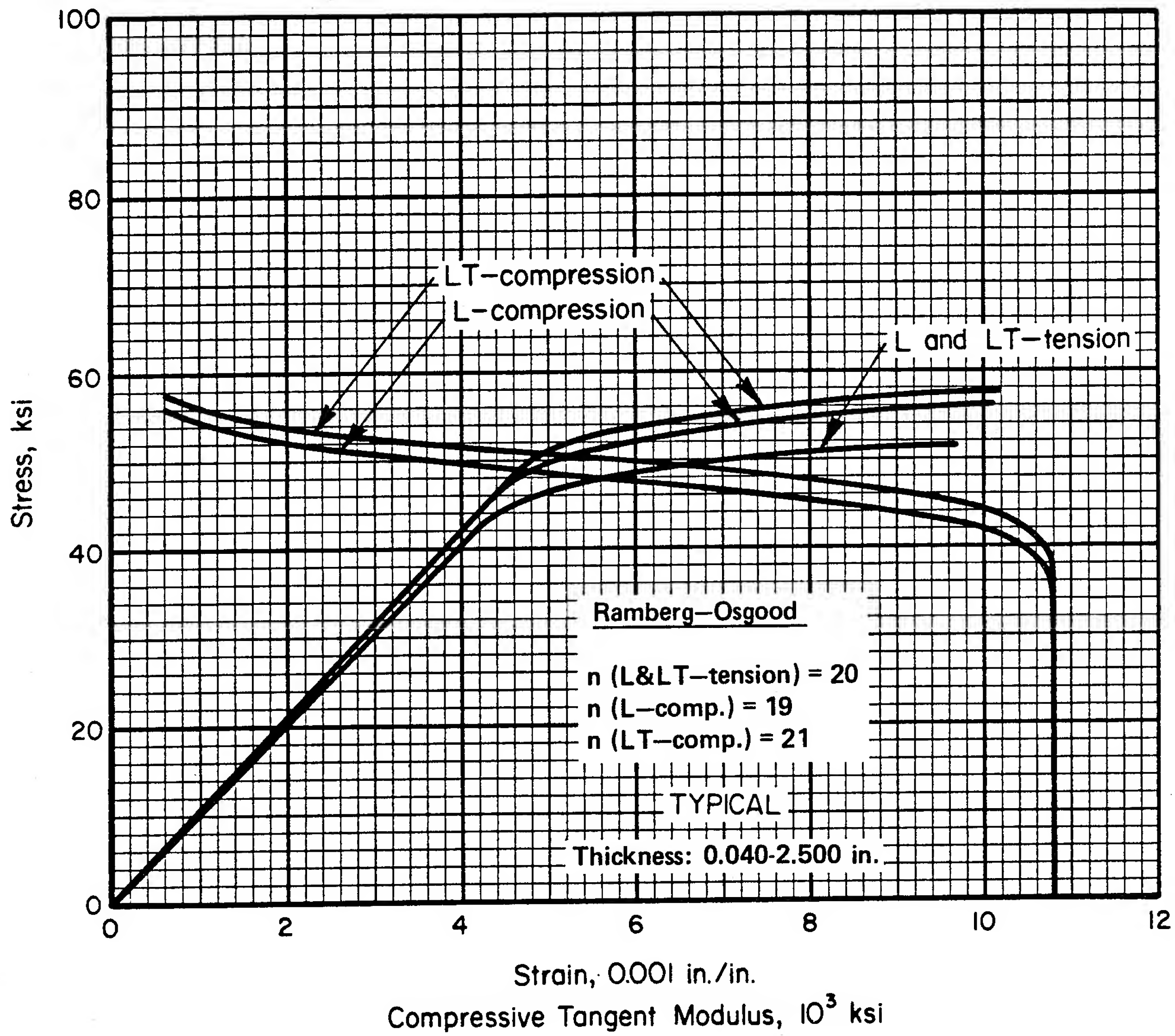

FIGURE 3.2.7.2.6(a). *Typical tensile and compressive stress-strain and compressive tangent-modulus curves for 2219-T81 aluminum alloy sheet and 2219-T851 aluminum alloy plate at room temperature.*

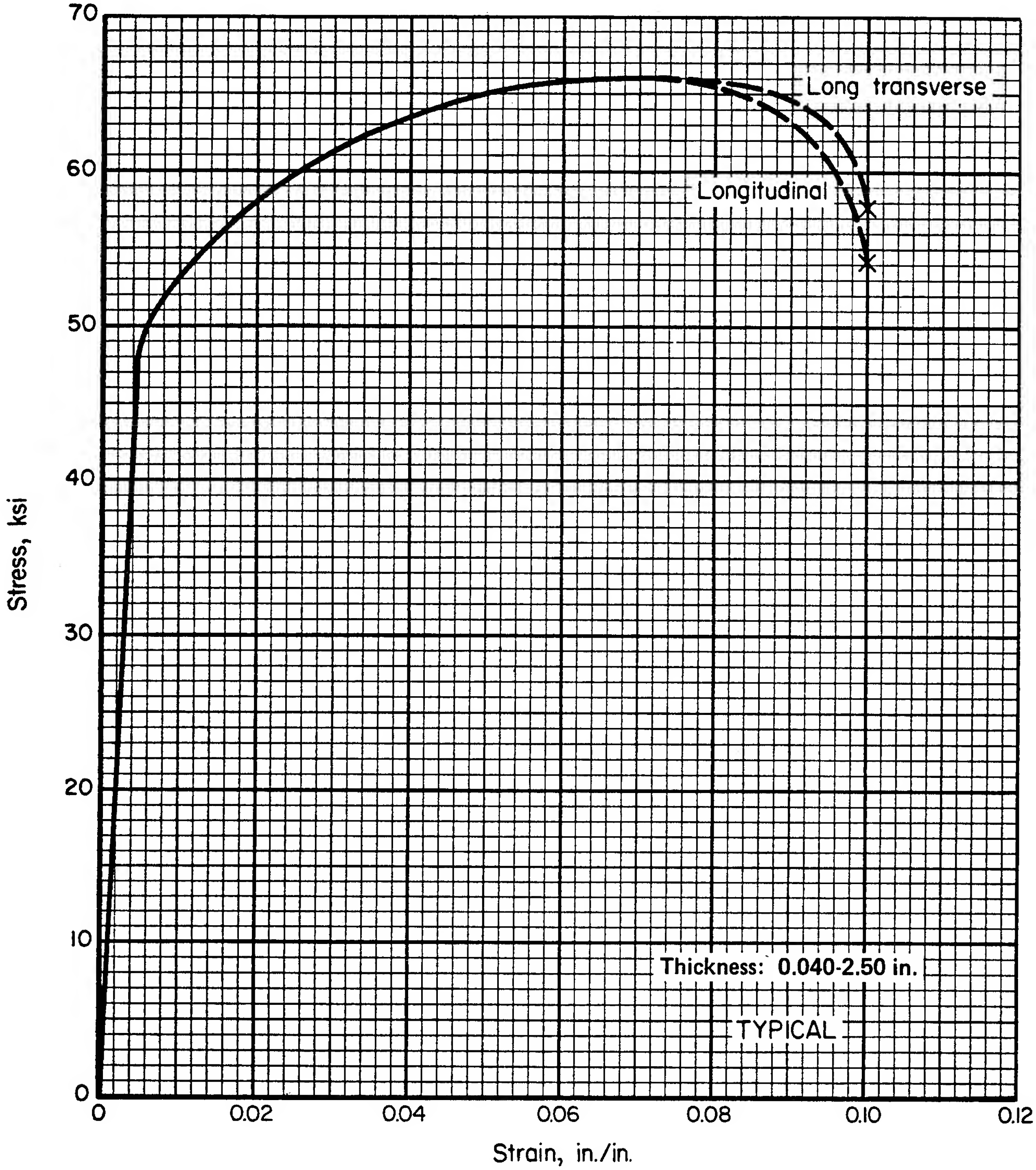

FIGURE 3.2.7.2.6(b). *Typical Tensile stress-strain curves (full-range) for 2219-T81 aluminum alloy sheet and 2219-T851 aluminum alloy plate at room temperature.*

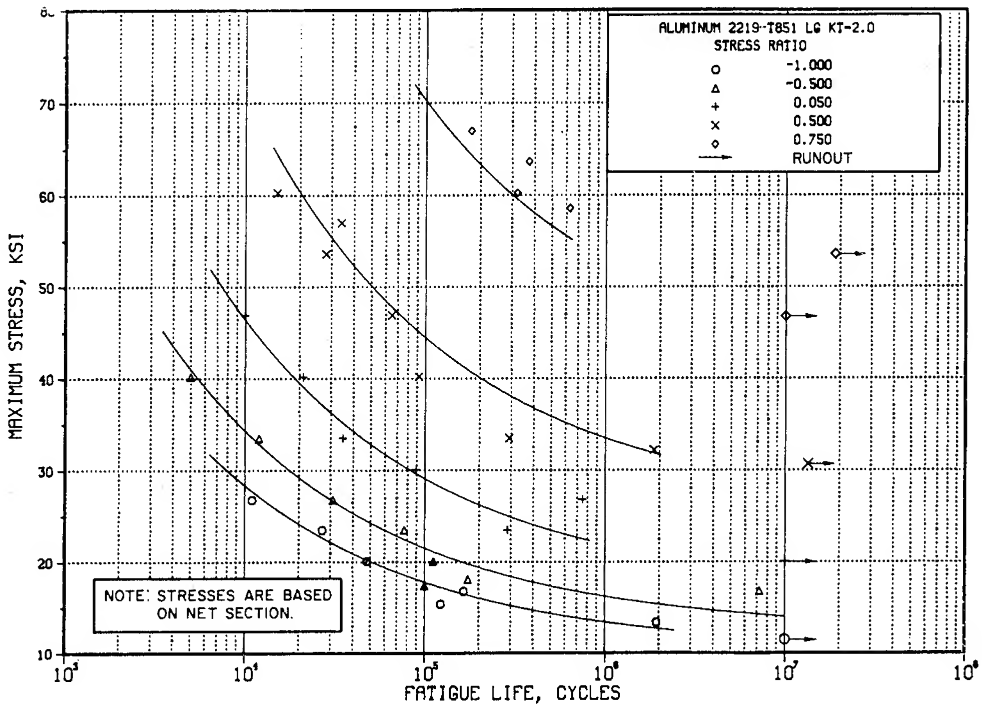

FIGURE 3.2.7.2.8(a). *Best-fit S/N curves for notched, K_t = 2.0, 2219-T851 aluminum alloy plate, longitudinal direction.*

Correlative Information for Figure 3.2.7.2.8(a)

Product Form: Plate, 2.00-inch thick

Properties:	TUS, ksi	TYS, ksi	Temp., F
	68	52	RT (unnotched)
	94	—	RT (notched)

Specimen Details: Notched, V-Groove, K_t = 2.0
0.195-inch gross diameter
0.136-inch net diameter
0.020-inch root radius, r
60° flank angle, ε

Surface Condition: As machined

Reference: 3.2.7.2.8

Test Parameters:

Loading – Axial
Frequency – 7000 to 8000 cpm
Temperature – RT
Environment – Air

No. of Heats/Lots: 1

Equivalent Stress Equation:

Log N_f = 7.92–2.69 log (S_{eq} – 16.0)
$S_{eq} = S_{max} (1-R)^{0.64}$ ksi
Standard Error of Estimate = 0.313
Standard Deviation in Life = 0.739
R^2 = 82%

Sample Size = 34

[Caution: The equivalent stress model may provide unrealistic life predictions for stress ratios beyond those represented above]

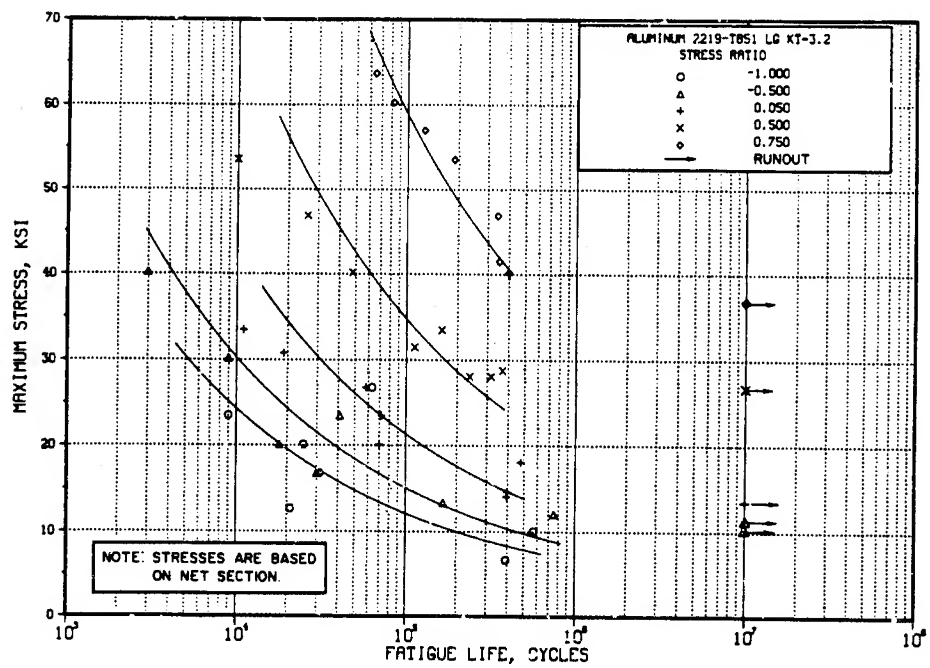

FIGURE 3.2.7.2.8(b). *Best-fit S/N curves for notched, K_t = 3.2, 2219-T851 aluminum alloy plate, longitudinal direction.*

Correlative Information for Figure 3.2.7.2.8(b)

Product Form: Plate, 2.00-inch thick

Properties:	TUS, ksi	TYS, ksi	Temp., F
	68	52	RT (unnotched)
	92	—	RT (notched)

Specimen Details: Notched, V-Groove, K_t = 3.2

0.195-inch gross diameter
0.136-inch net diameter
0.006-inch root radius, r
60° flank angle, ω

Surface Condition: As machined

Reference: 3.2.7.2.8

Test Parameters:

Loading - Axial
Frequency - 7000 to 8000 cpm
Temperature - RT
Environment - Air

No. of Heats/Lots: 1

Equivalent Stress Equation:

Log N_f = 8.46–2.83 log (S_{eq} - 3.93)
$S_{eq} = S_{max} (1-R)^{0.76}$
Standard Error of Estimate = 0.292
Standard Deviation in Life = 0.64
R^2 = 79%

Sample Size = 39

[Caution: The equivalent stress model may provide unrealistic life predictions for stress ratios beyond those represented above]

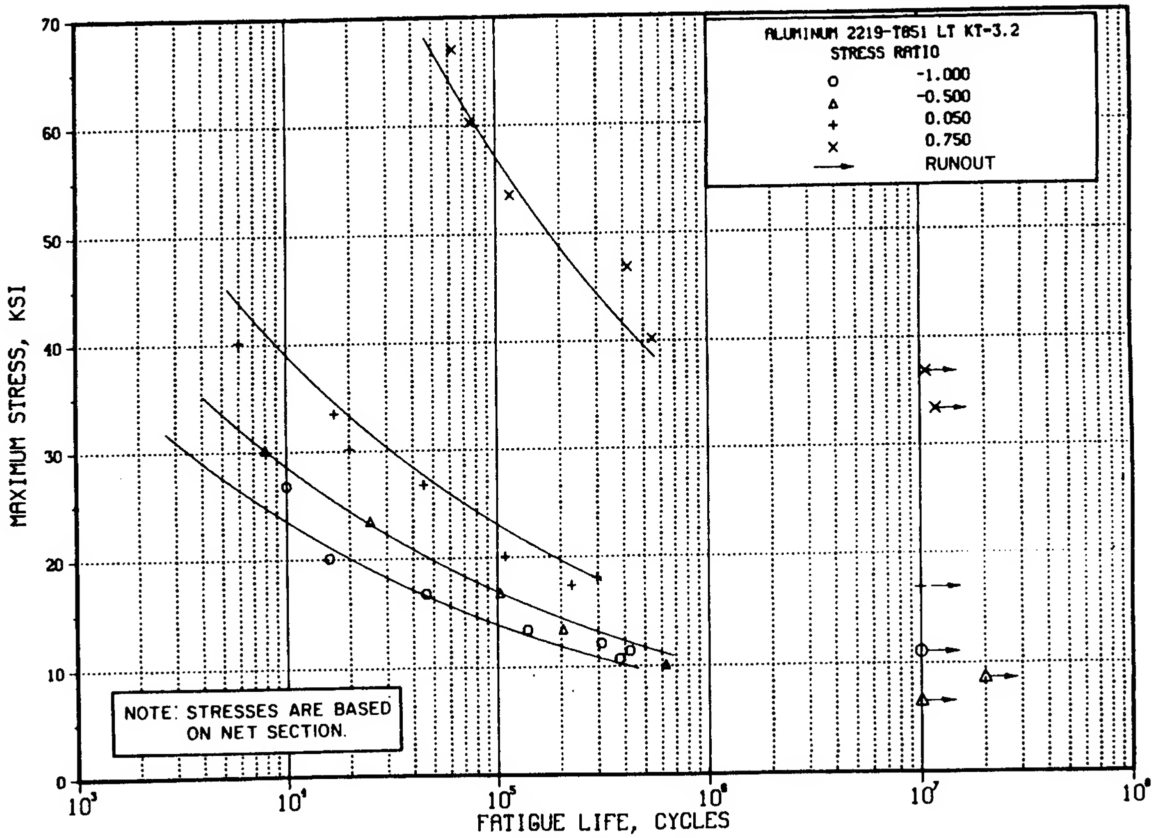

FIGURE 3.2.7.2.8(c). *Best-fit S/N curves for notched, K_t=3.2, 2219-T851 aluminum alloy plate, long transverse direction.*

Correlative Information for Figure 3.2.7.2 8(c)

Product Form: Plate, 2.00-inch thick

Properties:	TUS, ksi	TYS, ksi	Temp., F
	68	51	RT (unnotched)
	89	--	RT (notched)

Specimen Details: Notched, V-Groove, K_t=2.3
0.195-inch gross diameter
0.136-inch net diameter
0.006-inch root radius, r
60° flank angle, ω

Surface Condition: As machined

Reference: 3.2.7 2.8

Test Parameters:
Loading - Axial
Frequency - 7000 to 8000 cpm
Temperature - RT
Environment - Air

No. of Heats/Lots: 1

Equivalent Stress Equation:
Log N_f = 10.85-4.34 log (S_{eq})
$S_{eq} = S_{max} (1\text{-}R)^{0.686}$ ksi
Standard Error of Estimate = 0.153
Standard Deviation in Life = 0.610
R^2 = 94%

Sample Size = 25

[Caution: The equivalent stress model may provide unrealistic life predictions for stress ratios beyond those represented above]

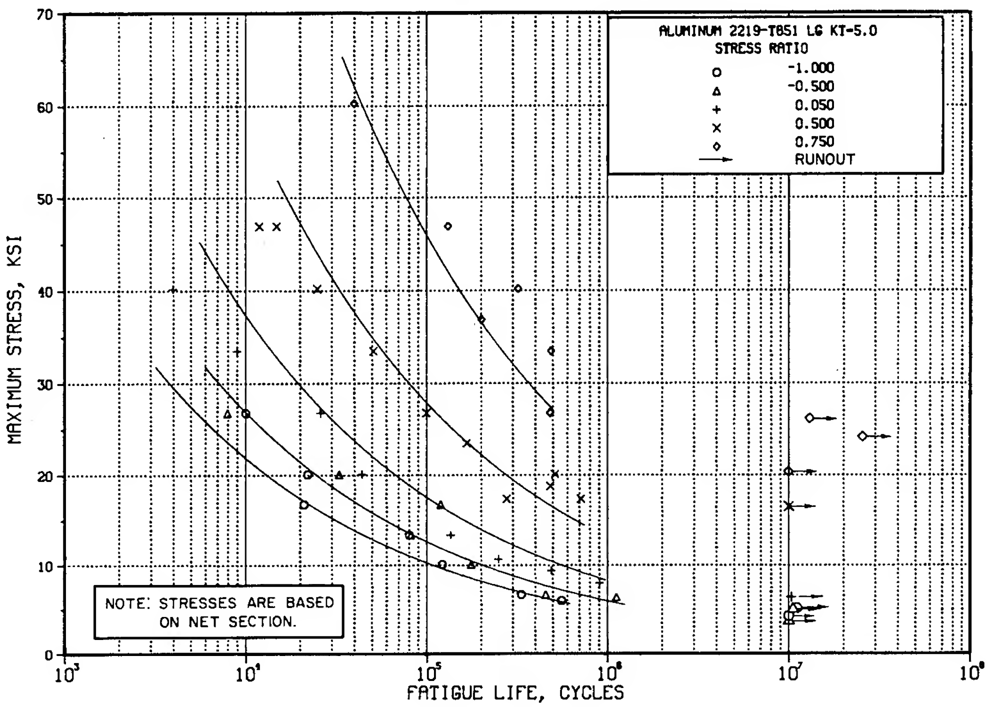

FIGURE 3.2.7.2.8(d). *Best-fit S/N curves for notched, K_t = 5.0, 2219-T851 aluminum alloy plate, longitudinal direction.*

Correlative Information for Figure 3.2.7.2.8(d)

Product Form: Plate, 2.00-inch thick

Properties:	TUS, ksi	TYS, ksi	Temp., F
	68 (L)	52 (L)	RT (unnotched)
	91 (L)	—	RT (notched)

Specimen Details: Notched, V-Groove, K_t = 5.0

0.300-inch gross diameter
0.210-inch net diameter
0.0035-inch root radius, r
60° flank angle, ω

Surface Condition: As machined

Reference: 3.2.7.2.8

Test Parameters:

Loading – Axial
Frequency – 7000 to 8000 cpm
Temperature – RT
Environment – Air

No. of Heats/Lots: 1

Equivalent Stress Equation:

$\log N_f = 8.76 - 3.05 \log (S_{eq})$
$S_{eq} = S_{max} (1-R)^{0.722}$ ksi
Standard Error of Estimate = 0.194
Standard Deviation in Life = 0.660
R^2 = 91%

Sample Size = 38

[Caution: The equivalent stress model may provide unrealistic life predictions for stress ratios beyond those represented above]

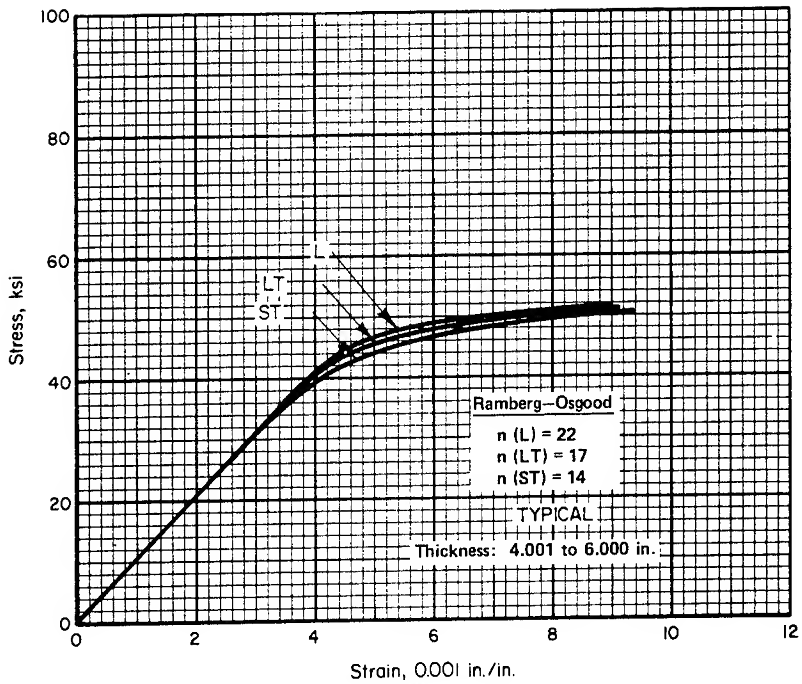

FIGURE 3.2.7.3.6(a). *Typical tensile stress-strain curves for 2219-T852 aluminum alloy hand forging at room temperature.*

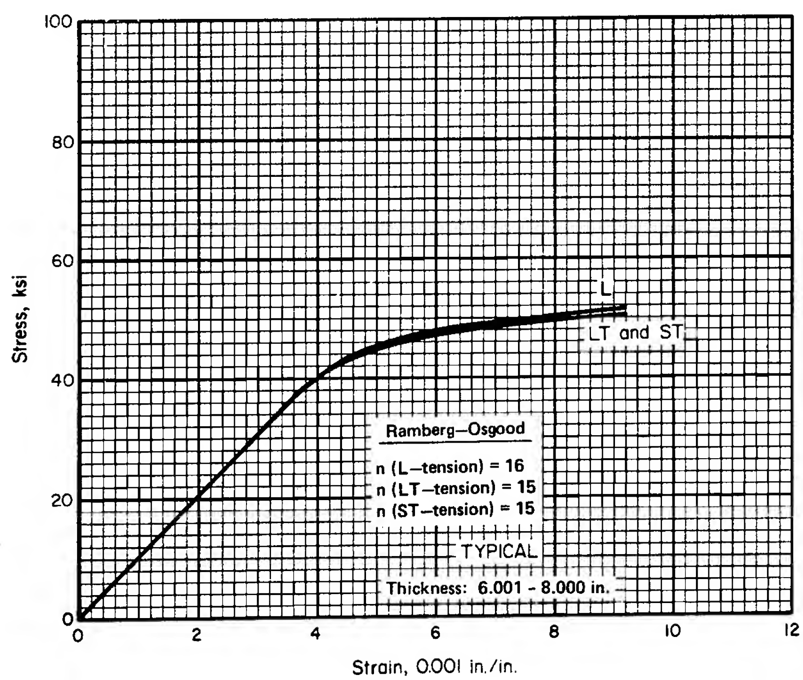

FIGURE 3.2.7.3.6(b). *Typical tensile stress-strain curves for 2219-T852 aluminum alloy hand forging at room temperature.*

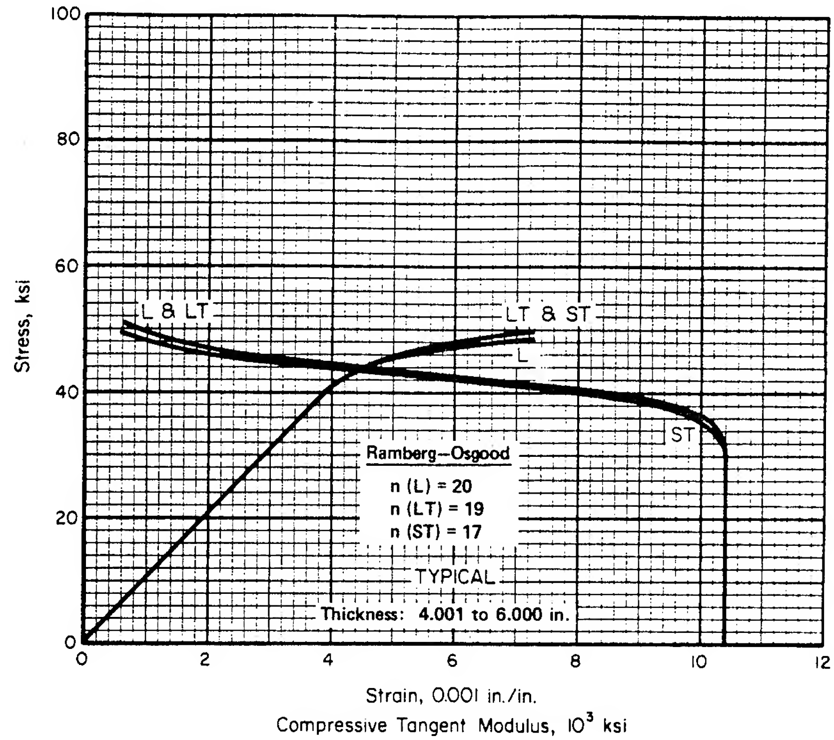

FIGURE 3.2.7.3.6(c). *Typical compressive stress-strain and compressive tangent-modulus curves for 2219-T852 aluminum alloy hand forging at room temperature.*

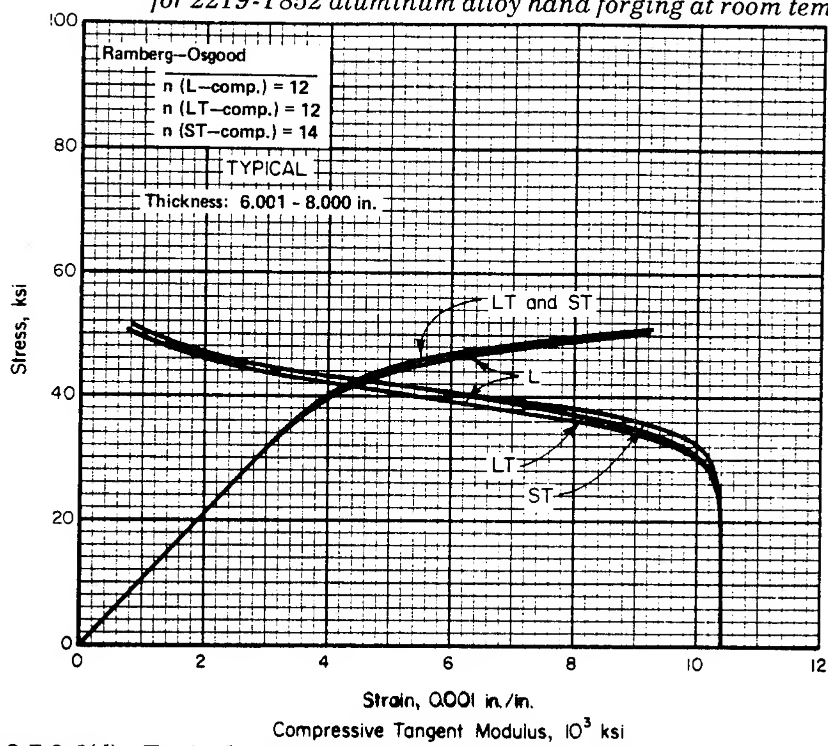

FIGURE 3.2.7.3.6(d). *Typical compressive stress-strain and compressive tangent-modulus curves for 2219-T852 aluminum alloy hand forging at room temperature.*

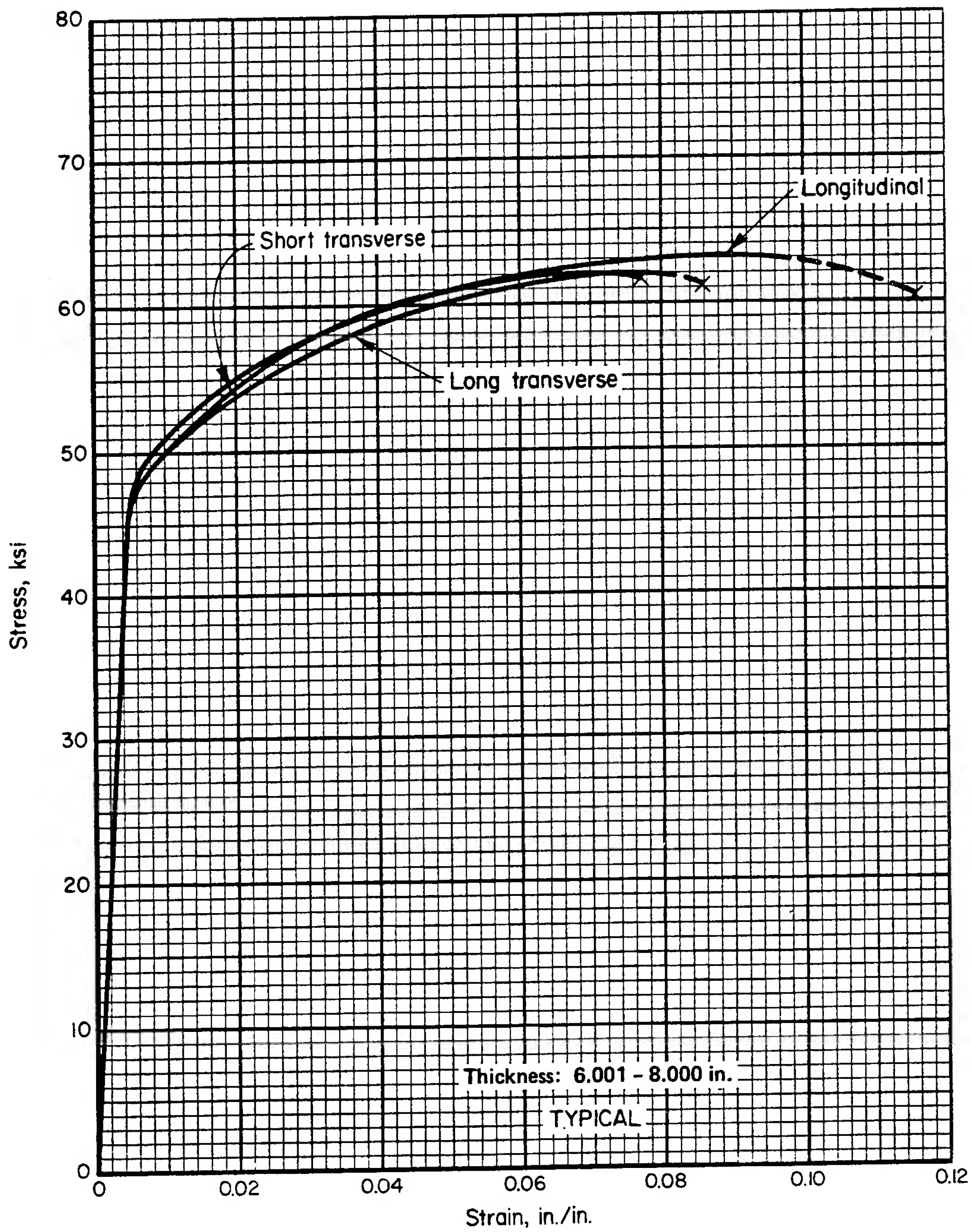

FIGURE 3.2.7.3.6(e). *Typical tensile stress-strain curves (full range) for 2219-T852 aluminum alloy hand forging at room temperature.*

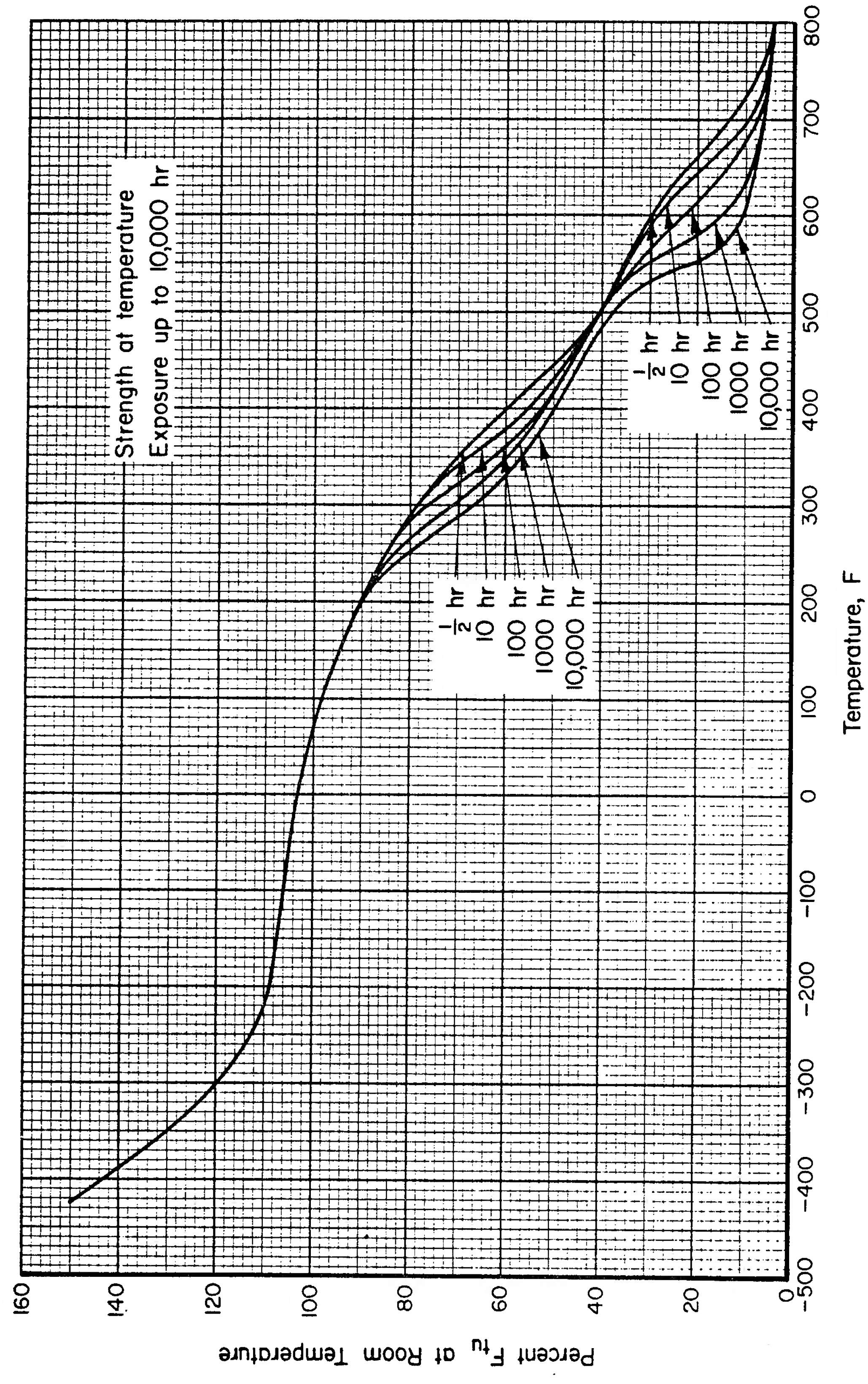

FIGURE 3.2.7.4.1(a). *Effect of temperature on the tensile ultimate strength (F_{tu}) of 2219-T87 aluminum alloy sheet and plate.*

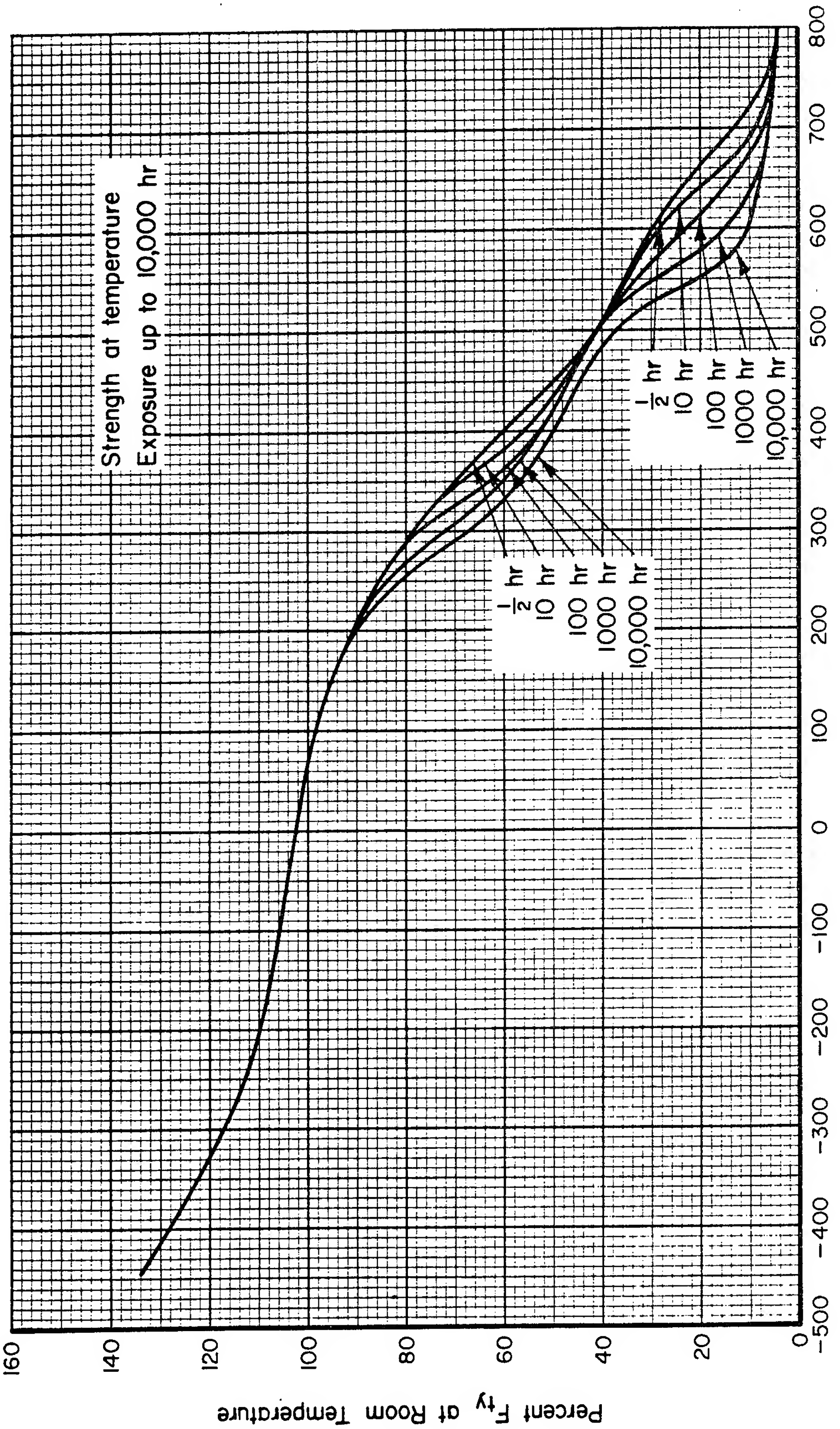

FIGURE 3.2.7.4.1(b). *Effect of temperature on the tensile yield strength (F_{ty}) of 2219-T87 aluminum alloy sheet and plate.*

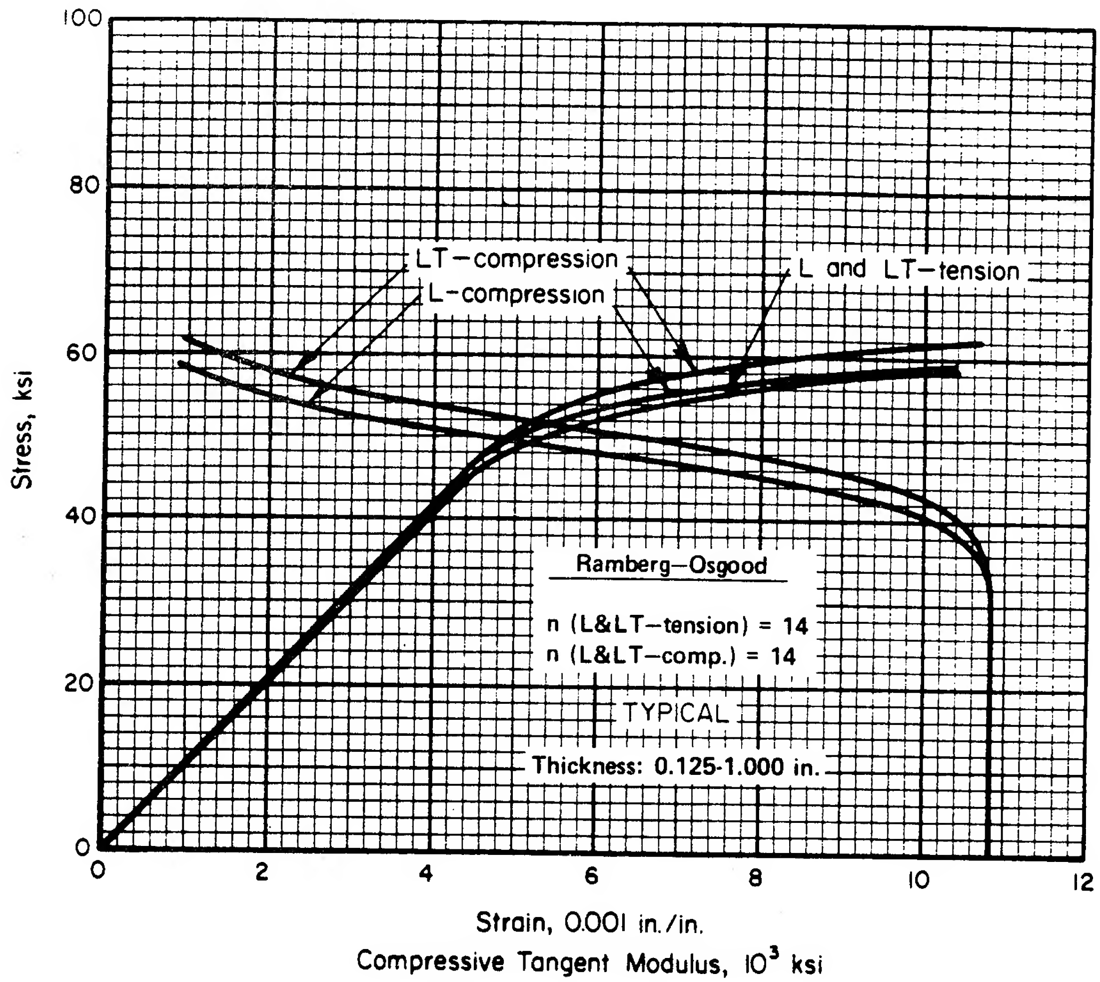

FIGURE 3.2.7.4.6(a). *Typical tensile and compressive stress-strain and compressive tangent-modulus curves for 2219-T87 aluminum alloy sheet and plate at room temperature.*

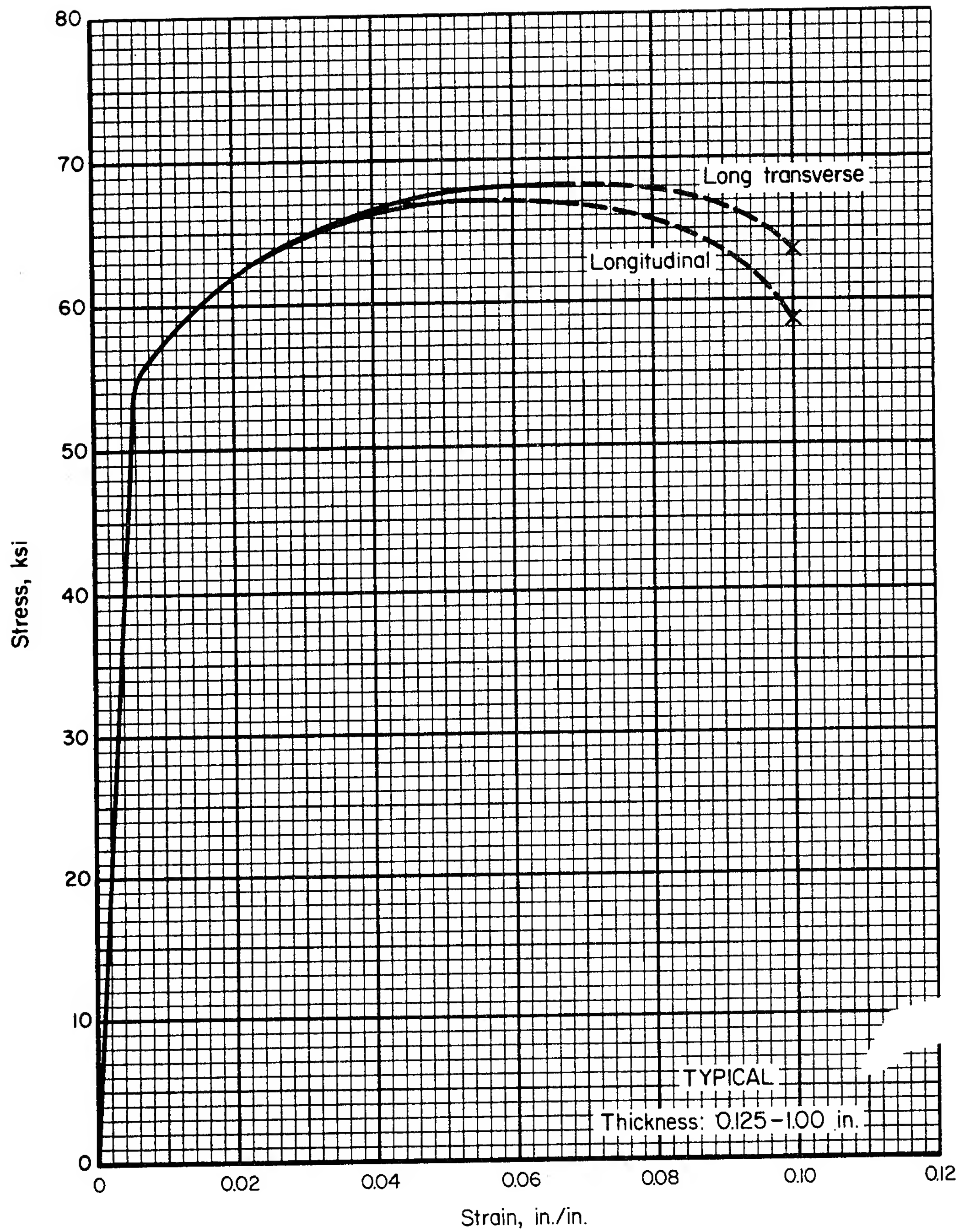

FIGURE 3.2.7.4.6(b). *Typical tensile stress-strain curves (full range) for 2219-T87 aluminum alloy sheet and plate at room temperature.*

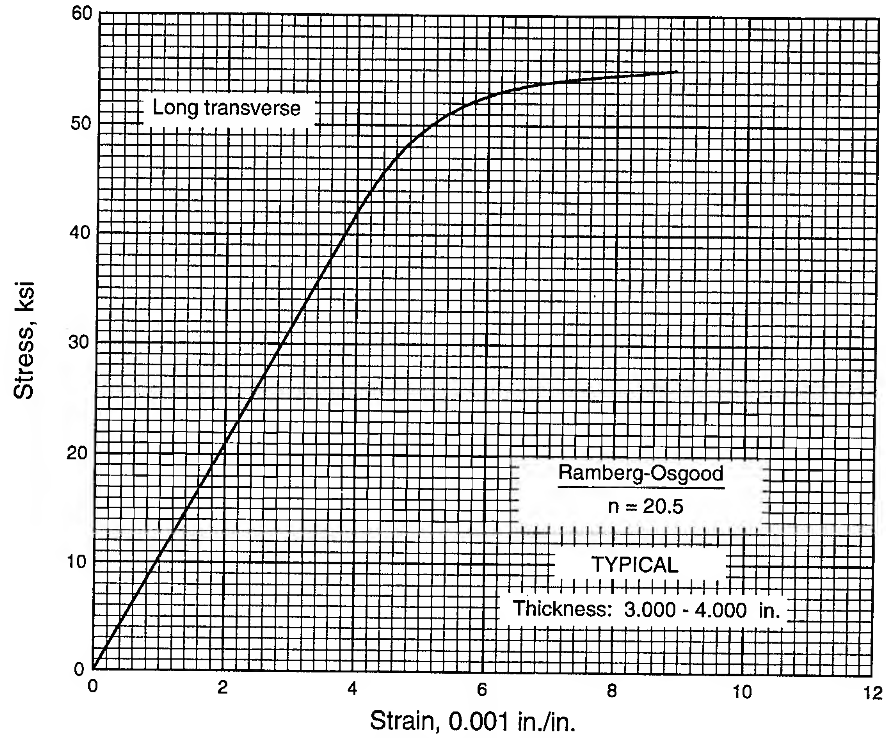

FIGURE 3.2.7.4.6(c). *Typical tensile stress-strain curve (full-range) for 2219-T87 aluminum alloy plate at room temperature.*

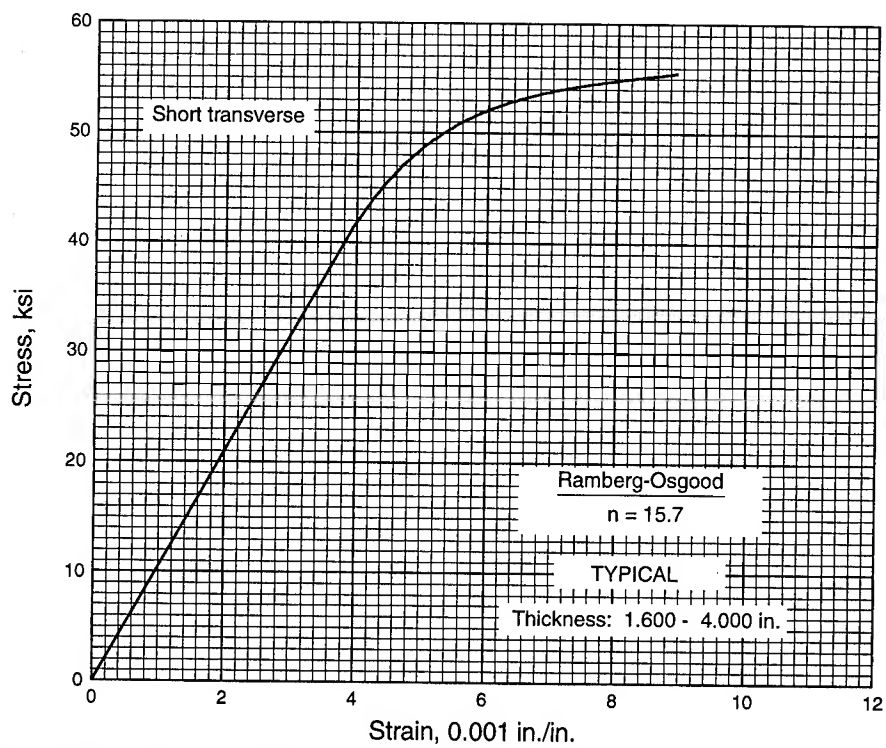

FIGURE 3.2.7.4.6(d). *Typical tensile stress-strain curve (full-range) for 2219-T87 aluminum alloy plate at room temperature.*

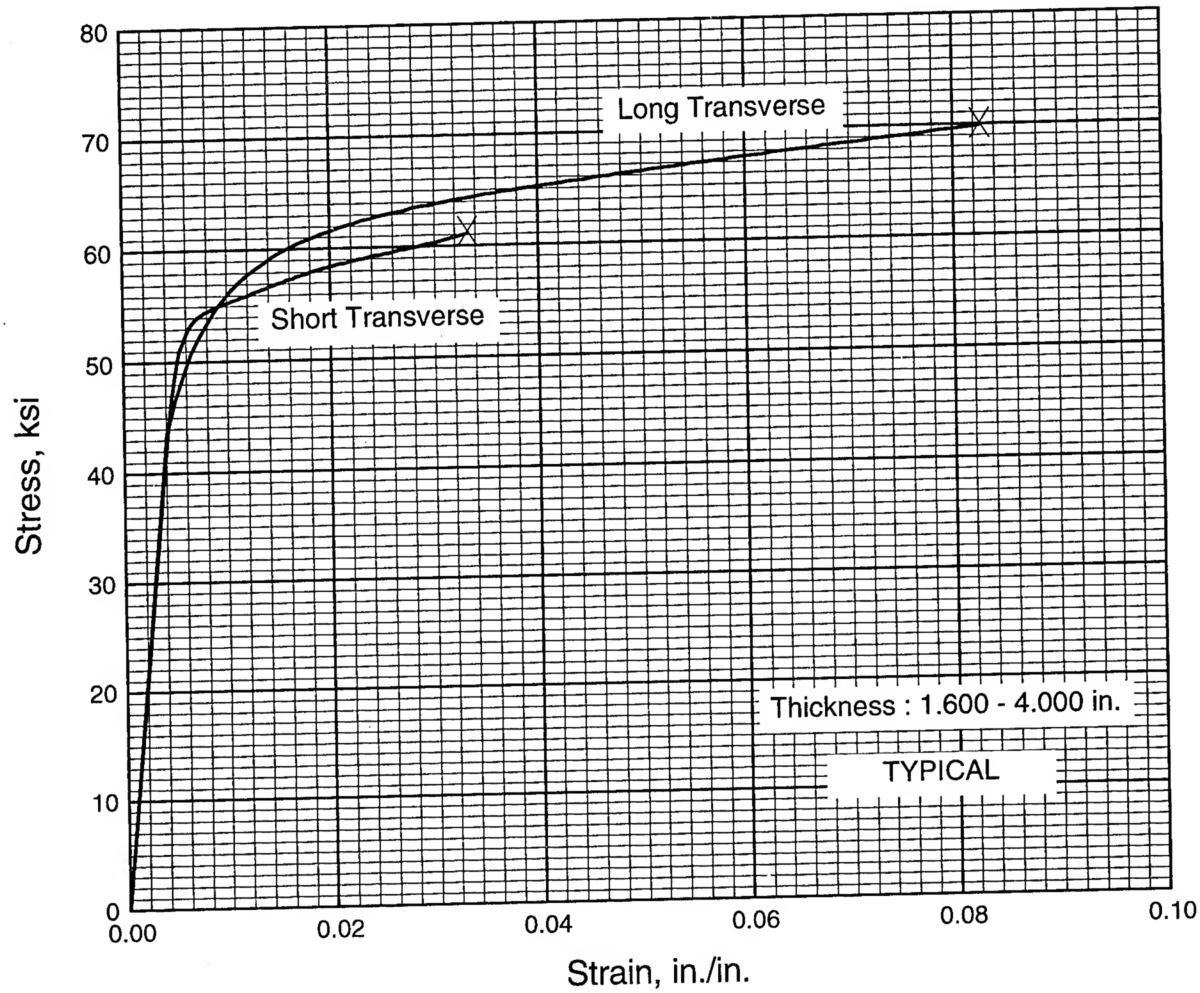

FIGURE 3.2.7.4.6(e). *Typical tensile stress-strain curve (full-range) for 2219-T87 aluminum alloy plate at room temperature.*

3.2.8 2519 ALLOY

3.2.8.0 *Comments and Properties.*—2519 is an Al-Cu weldable alloy available in plate. This armor plate has equivalent ballistic protection characteristics compared to 7039 and superior stress-corrosion cracking resistance compared to 5083. See Section 3.1.2.3 for comments regarding resistance of the alloy to stress-corrosion cracking. The general corrosion characteristics of 2519 are similar to 2219. 2519 in the T87 temper has approximately 20 percent higher yield strength than 2219-T87 plate. 2519-T87 is easily welded with filler alloy 2319. Yield strengths of welded butt joints are higher than other commercially available alloys. 2519 can be post weld aged or post weld heat treated and aged to obtain improved mechanical properties compared to "as welded" condition. See Section 3.1.3.4 for further information regarding the weldability of the alloy.

A material specification of 2519 is presented in Table 3.2.8.0(a). Room-temperature mechanical and physical properties are shown in Table 3.2.8.0(b).

TABLE 3.2.8.0(a). *Material Specification for 2519 Aluminum Alloy*

Specification	Form
MIL-A-46192	Plate

The temper index for 2519 is as follows:

Section	Temper
3.2.8.1	T87

3.2.8.1 *T87 Temper.*—Typical room-temperature tensile and compressive stress-strain and compressive tangent-modulus curves are presented in Figures 3.2.8.1.6(a) and (b).

TABLE 3.2.8.0(b). *Design Mechanical and Physical Properties of 2519 Aluminum Alloy Plate*

Specification	MIL-A-46192			
Form	Plate			
Temper	T87			
Thickness or diameter, in.	0.250-1.000	1.001-2.000	2.001-3.000	3.001-4.000
Basis	S	S	S	S
Mechanical Properties:				
F_{tu}, ksi:				
L	65	65	65	65
LT	66	66	66	66
ST	...	...	61	60
F_{ty}, ksi:				
L	59	59	59	59
LT	58	58	58	58
ST	...	...	54	54
F_{cy}, ksi:				
L	57	57	57	57
LT	60	60	60	60
ST	...	...	57	57
F_{su}, ksi	41	40	40	39
F_{bru}[a], ksi:				
(e/D = 1.5)	103	102	101	100
(e/D = 2.0)	132	130	129	127
F_{bry}[a], ksi:				
(e/D = 1.5)	85	85	85	85
(e/D = 2.0)	99	99	89	99
e, percent:				
LT	6	5	4	3
E, 10^3 ksi	10.5			
E_c, 10^3 ksi	10.8			
G, 10^3 ksi	4.0			
μ	0.33			
Physical Properties:				
ω, lb/in.^{3}	0.102			
C, K, and α	...			

[a]See Table 3.1.2.1.1. Bearing values are "dry pin" per Section 1.4.7.1.

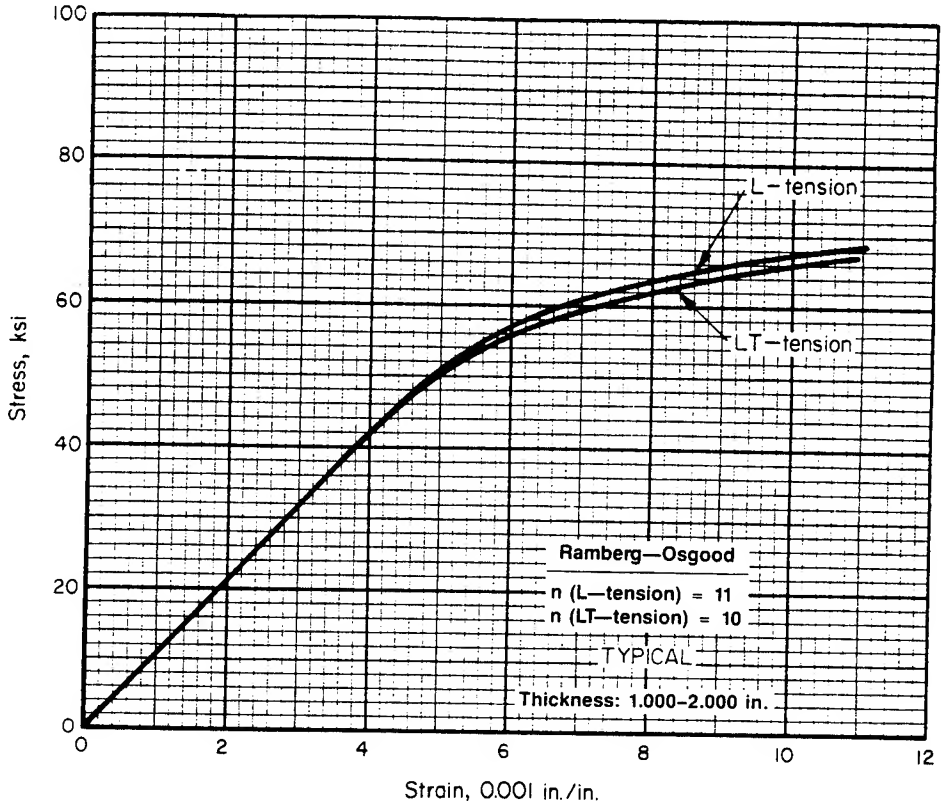

FIGURE 3.2.8.1.6(a). *Typical tensile stress-strain curves for 2519-T87 aluminum alloy plate at room temperature.*

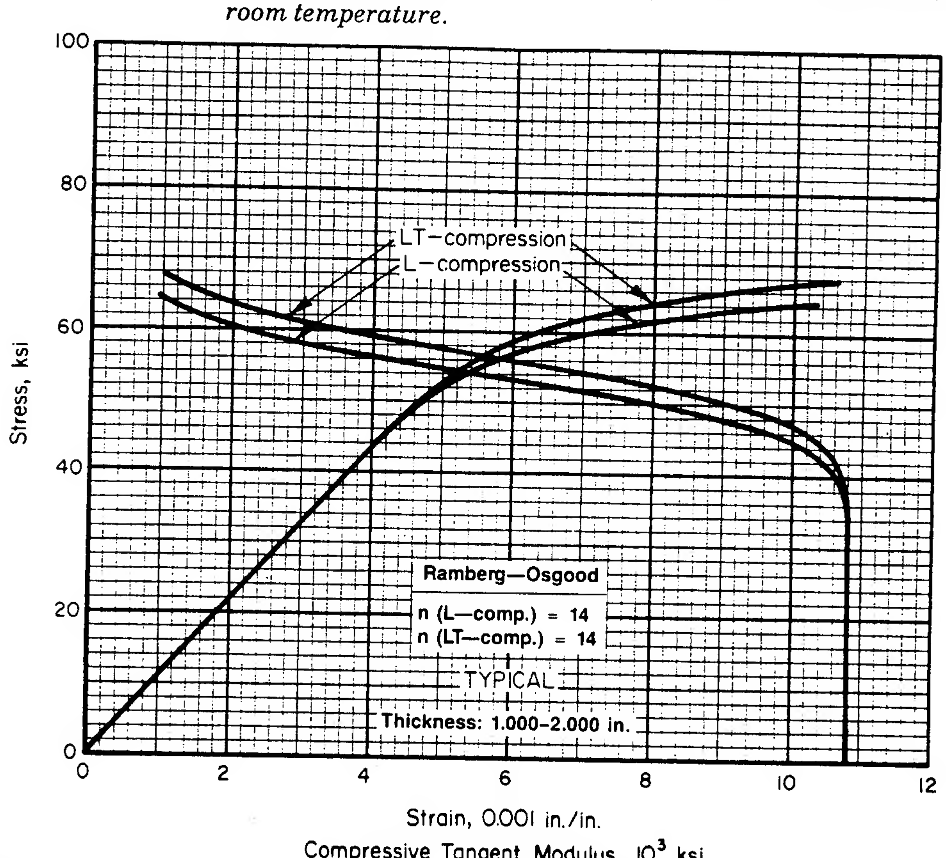

FIGURE 3.2.8.1.6(b). *Typical compressive stress-strain and tangent-modulus curves for 2519-T87 plate at room temperature.*

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3.2.9 2618 ALLOY

3.2.9.0 *Comments and Properties.*—2618 is an Al-Cu alloy which has been used principally for hand and die forgings. It has excellent properties over a range of temperatures from -452 to 600 F and is usually used in applications where high strength and creep resistance are important considerations. Refer to Section 3.1.3.4 for comments regarding the weldability of the alloy. Refer to Section 3.1.2.3.1 for information regarding resistance of the alloy to stress-corrosion cracking.

Material specifications for 2618 aluminum alloy are presented in Table 3.2.9.0(a). Room-temperature mechanical and physical properties are shown in Table 3.2.9.0(b) and (c). The effect of temperature on the thermal expansion is shown in Figure 3.2.9.0

TABLE 3.2.9.0(a). *Material Specifications for 2618 Aluminum Alloy*

Specification	Form
AMS 4132	Die and hand forgings
QQ-A-367	Forgings
MIL-A-22771	Die forging

The temper index for 2618 is as follows:

Section	Temper
3.2.9.1	T61

3.2.9.1 *T61 Temper.*—Figures 3.2.9.1.1(a) through 3.2.9.1.5 present effect-of-temperature curves for various mechanical properties. Figure 3.2.9.1.6(a) presents tensile and compressive stress-strain and tangent-modulus curves at room temperature. Figure 3.2.9.1.6(b) is a full-range, tensile stress-strain curve at room temperature.

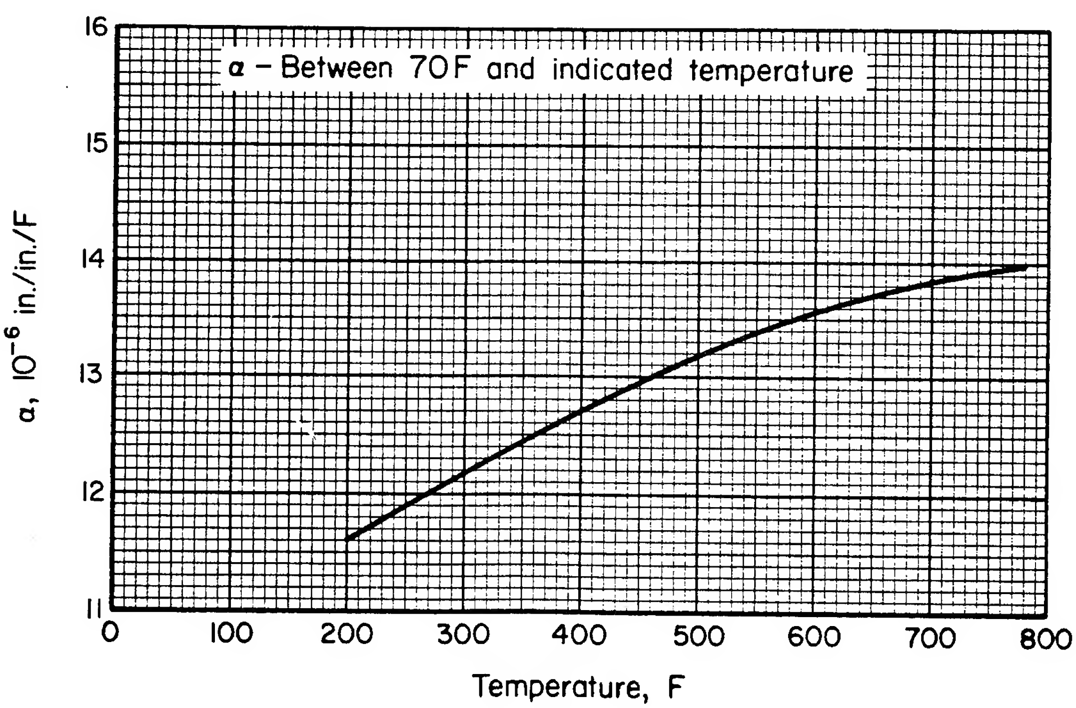

FIGURE 3.2.9.0. *Effect of temperature on the thermal expansion of 2618 aluminum alloy.*

TABLE 3.2.9.0(b). *Design Mechanical and Physical Properties of 2618 Aluminum Alloy Die Forging*

Specification	MIL-A-22771 and QQ-A-367
Form	Die forging
Temper	T61
Thickness, in.	≤ 4.000[a]
Basis	S
Mechanical Properties:	
F_{tu}, ksi:	
L	58
T[b]	55
F_{ty}, ksi:	
L	45
T[b]	42
F_{cy}, ksi:	
L	...
T[b]	...
F_{su}, ksi......................	...
F_{bru}, ksi:	
(e/D = 1.5)	...
(e/D = 2.0)	...
F_{bry}, ksi:	
(e/D = 1.5)	...
(e/D = 2.0)	...
e, percent:	
L	4
T[b]	4
E, 10^3 ksi	10.7
E_c, 10^3 ksi	10.9
G, 10^3 ksi	4.1
μ	0.33
Physical Properties:	
ω, lb/in.^{3}	0.100
C, Btu/(lb)(F)	0.23 (at 212 F)
K, Btu/[(hr)(ft^3)(F)/ft]	90 (at 77 F)
α, 10^{-6} in./in./F	See Figure 3.2.9.0

[a]Thickness at the time of heat treatment. When die forgings are machined before heat treatment, the mechanical properties are applicable provided the as-forged thickness is not greater than twice the thickness at the time of heat treatment.
[b]For die forgings, T indicates any grain direction not within ±15° of being parallel to the forging flow lines. Specimens to test transverse properties should be located as close to the short transverse direction as possible.

TABLE 3.2.9.0(c). *Design Mechanical and Physical Properties of 2618 Aluminum Alloy Hand Forging*

Specification	AMS 4132, MIL-A-22771, and QQ-A-367		
Form	Hand forging		
Temper	T61		
Cross-sectional area, in.^{2}	≤ 144		
Thickness,[a] in.	< 2.000	2.000-3.000	3.001-4.000
Basis	S	S	S
Mechanical Properties:			
F_{tu}, ksi:			
L	58	57	56
LT	55	55	53
ST	...	52	51
F_{ty}, ksi:			
L	47	36	45
LT	42	42	40
ST	...	42	39
F_{cy}, ksi:			
L	...	...	44
LT	...	...	42
ST	...	...	40
F_{su}, ksi	...	...	33
F_{bru}, ksi:			
(e/D = 1.5)	...	...	...
(e/D = 2.0)	...	...	106
F_{bry}, ksi:			
(e/D = 1.5)	...	...	...
(e/D = 2.0)	...	...	71
e, percent:			
L	7	7	7
LT	5	5	5
ST	...	4	4
E, 10^3 ksi	10.7		
E_c, 10^3 ksi	10.9		
G, 10^3 ksi	4.1		
μ	0.33		
Physical Properties:			
ω, lb/in.^{3}	0.100		
C, Btu/(lb)(F)	0.23 (at 212 F)		
K, Btu/[(hr)(ft^2)(F)/ft]	90 (at 77 F)		
α, 10^{-6} in./in./F	See Figure 3.2.9.0		

[a]When hand forgings are machined before heat treatment, the section thickness at time of heat treatment shall determine the minimum mechanical properties as long as the original (as-forged) thickness does not exceed the maximum thickness for the alloy as shown in the table.

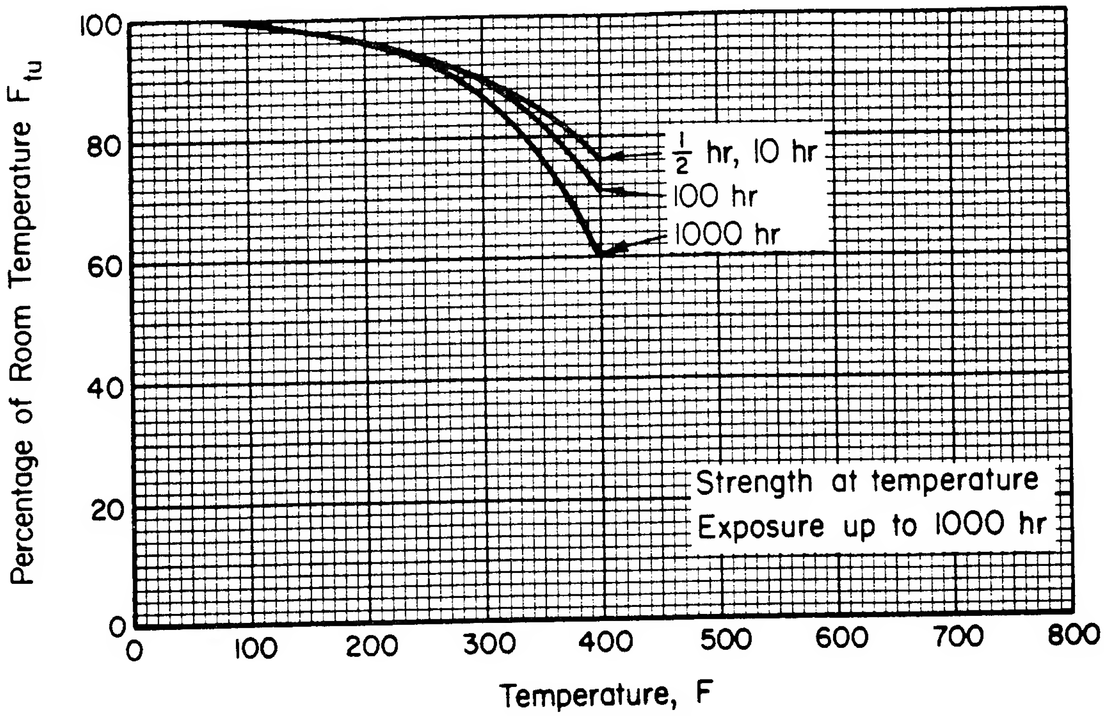

FIGURE 3.2.9.1.1(a). *Effect of temperature on the tensile ultimate strength (F_{tu}) of 2618-T61 aluminum alloy hand forging.*

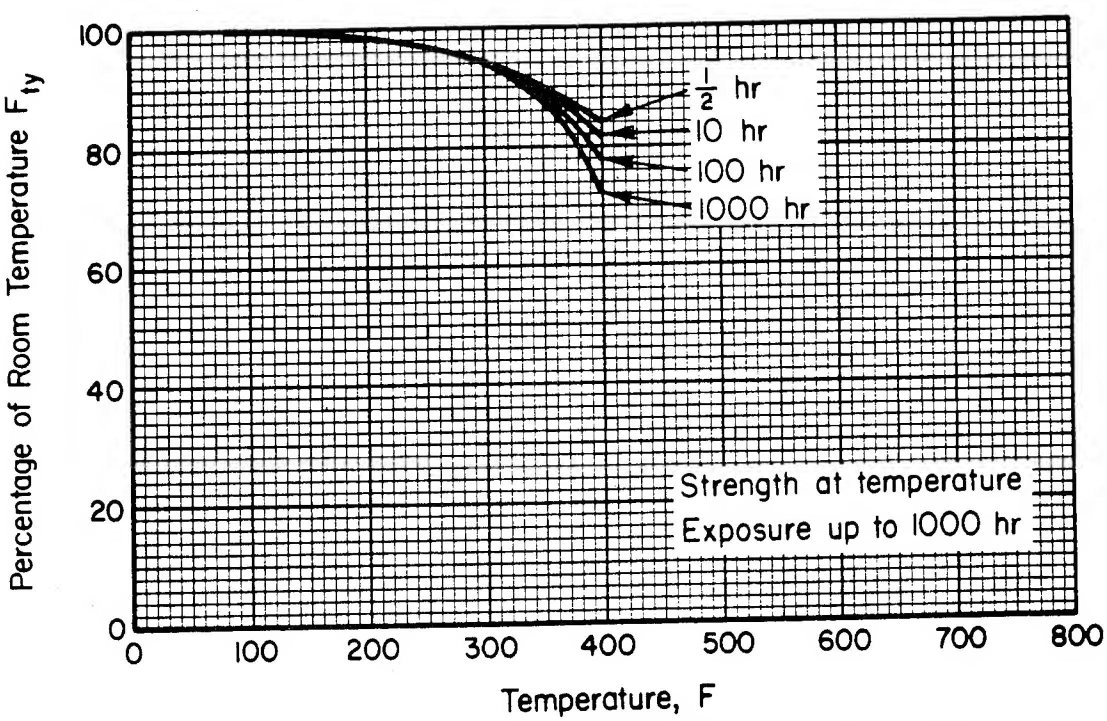

FIGURE 3.2.9.1.1(b). *Effect of temperature on the tensile yield strength (F_{ty}) of 2618-T61 aluminum alloy hand forging.*

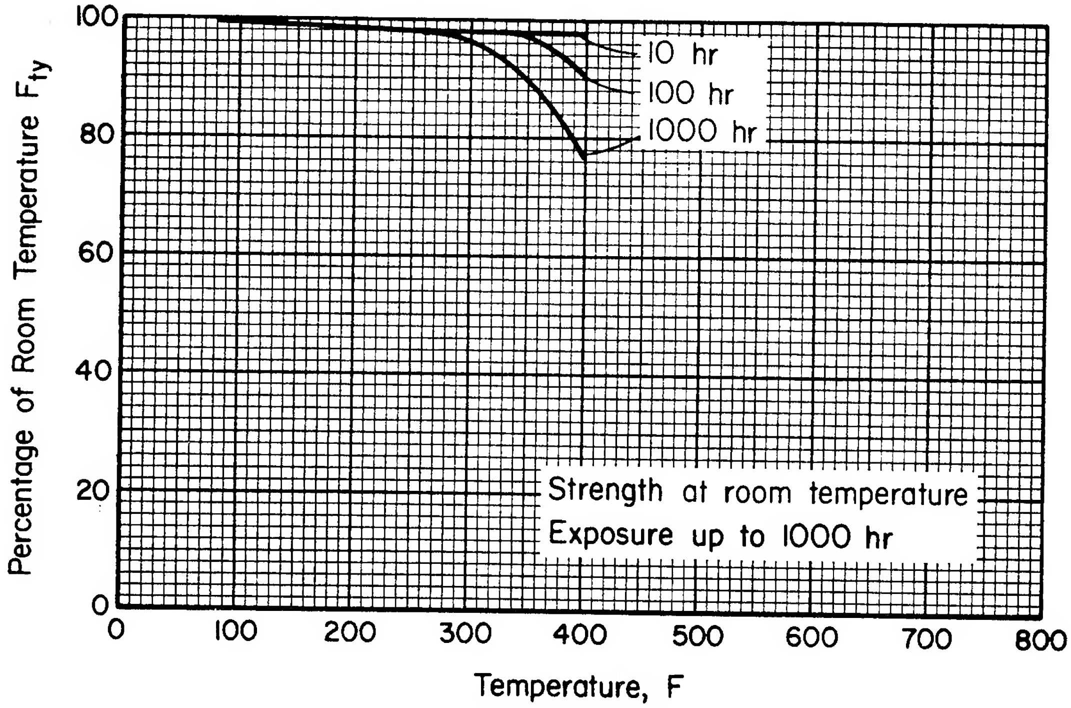

FIGURE 3.2.9.1.1(c). *Effect of exposure at elevated temperatures on room-temperature tensile yield strength (F_{ty}) of 2618-T61 hand forging.*

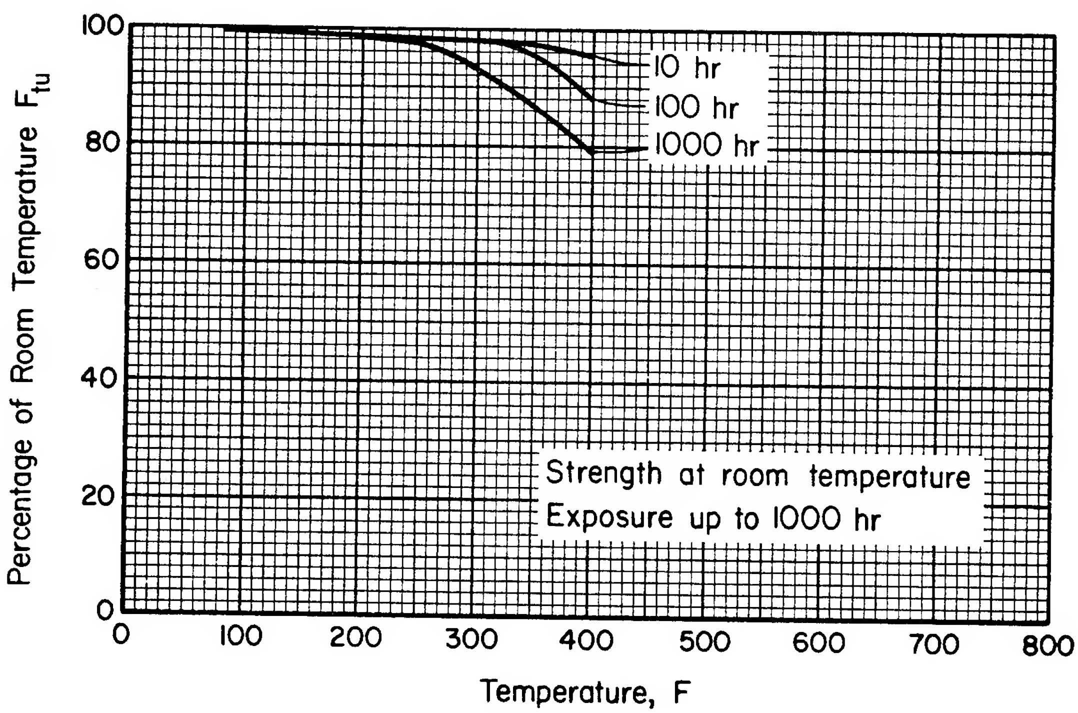

FIGURE 3.2.9.1.1(d). *Effect of exposure at elevated temperatures on room-temperature tensile ultimate strength (F_{tu}) of 2618-T61 hand forging.*

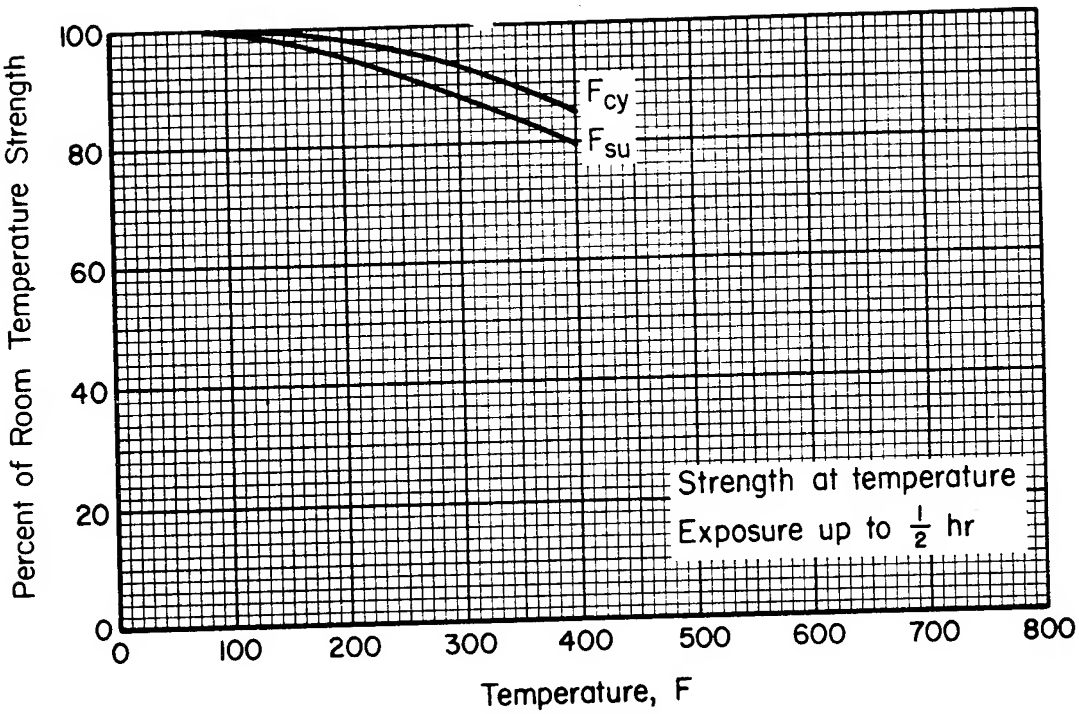

FIGURE 3.2.9.1.2. *Effect of temperature on the compressive yield strength (F_{cy}) and ultimate shear strength (F_{su}) of 2618-T61 aluminum alloy hand forging.*

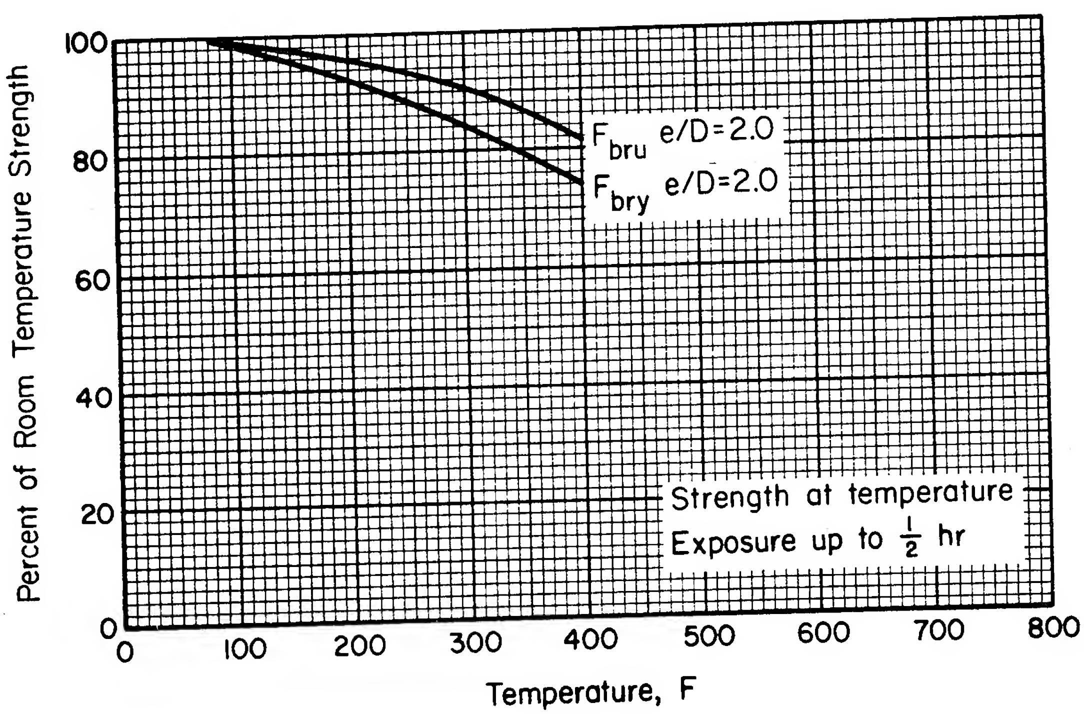

FIGURE 3.2.9.1.3. *Effect of temperature on the ultimate bearing strength (F_{bru}) and bearing yield strength (F_{bry}) of 2618-T61 aluminum alloy hand forging.*

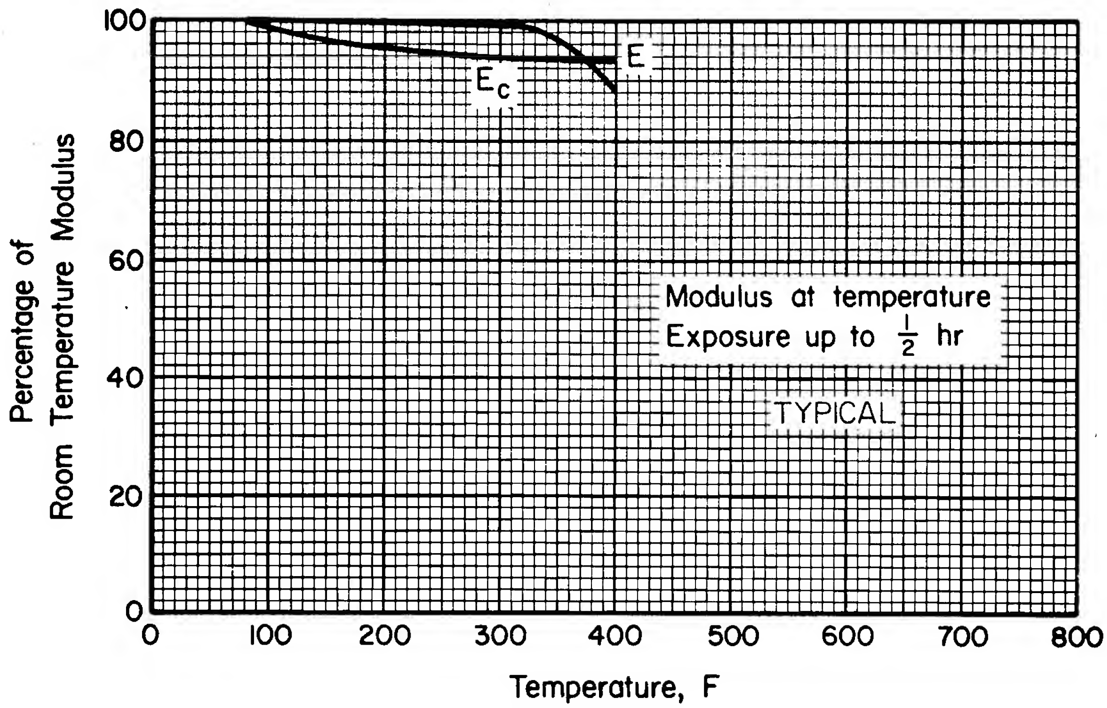

FIGURE 3.2.9.1.4. *Effect of temperature on the tensile and compressive moduli (E and E_c) of 2618-T61 aluminum alloy hand forging.*

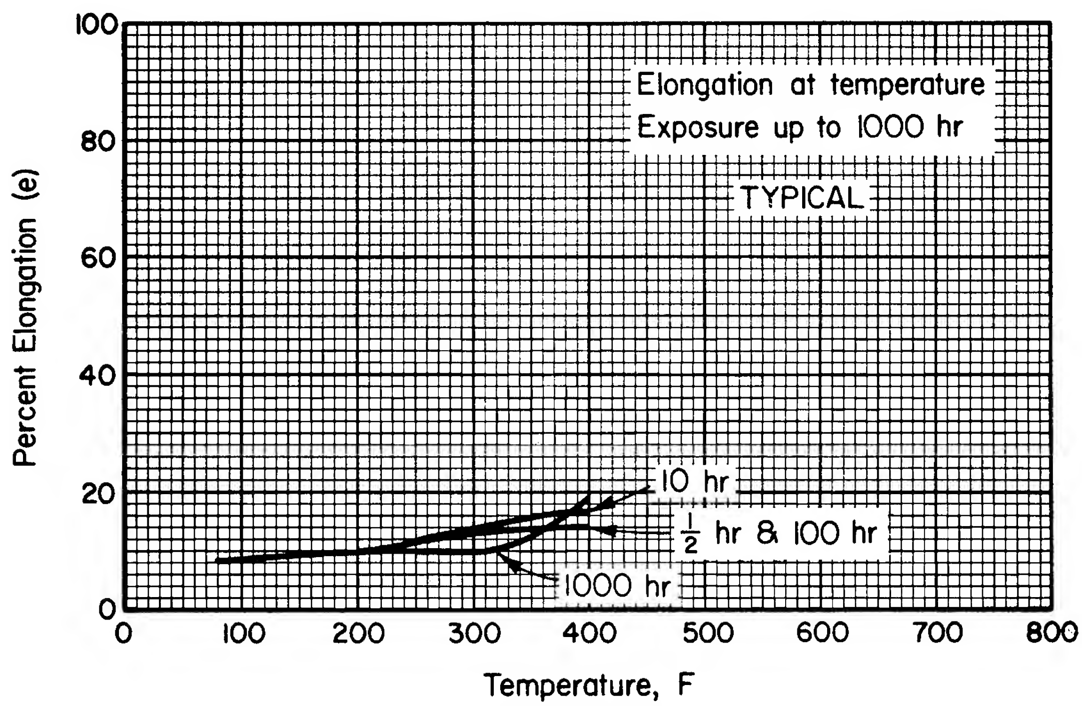

FIGURE 3.2.9.1.5. *Effect of temperature on the elongation (e) of 2618-T61 aluminum alloy hand forging.*

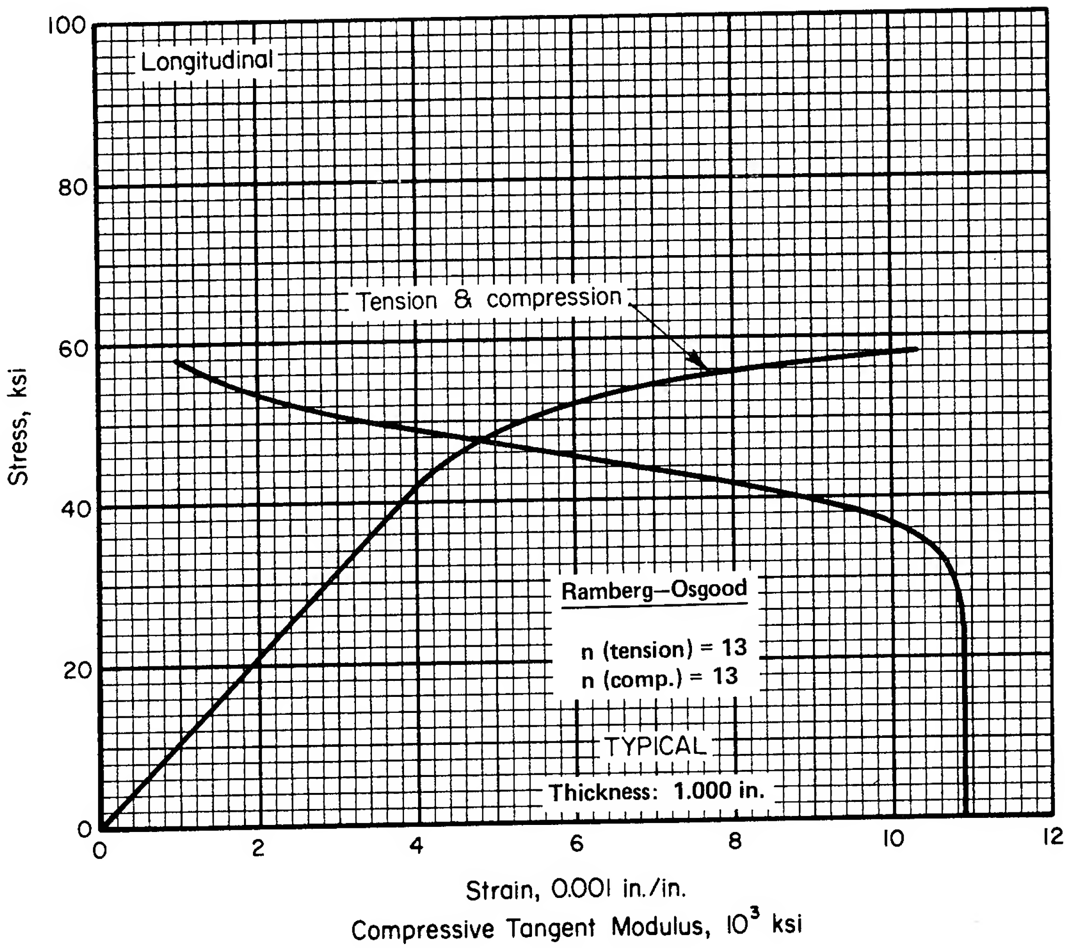

FIGURE 3.2.9.1.6(a). *Typical tensile and compressive stress-strain and compressive tangent-modulus curves for 2618-T61 aluminum alloy forged bar at room temperature.*

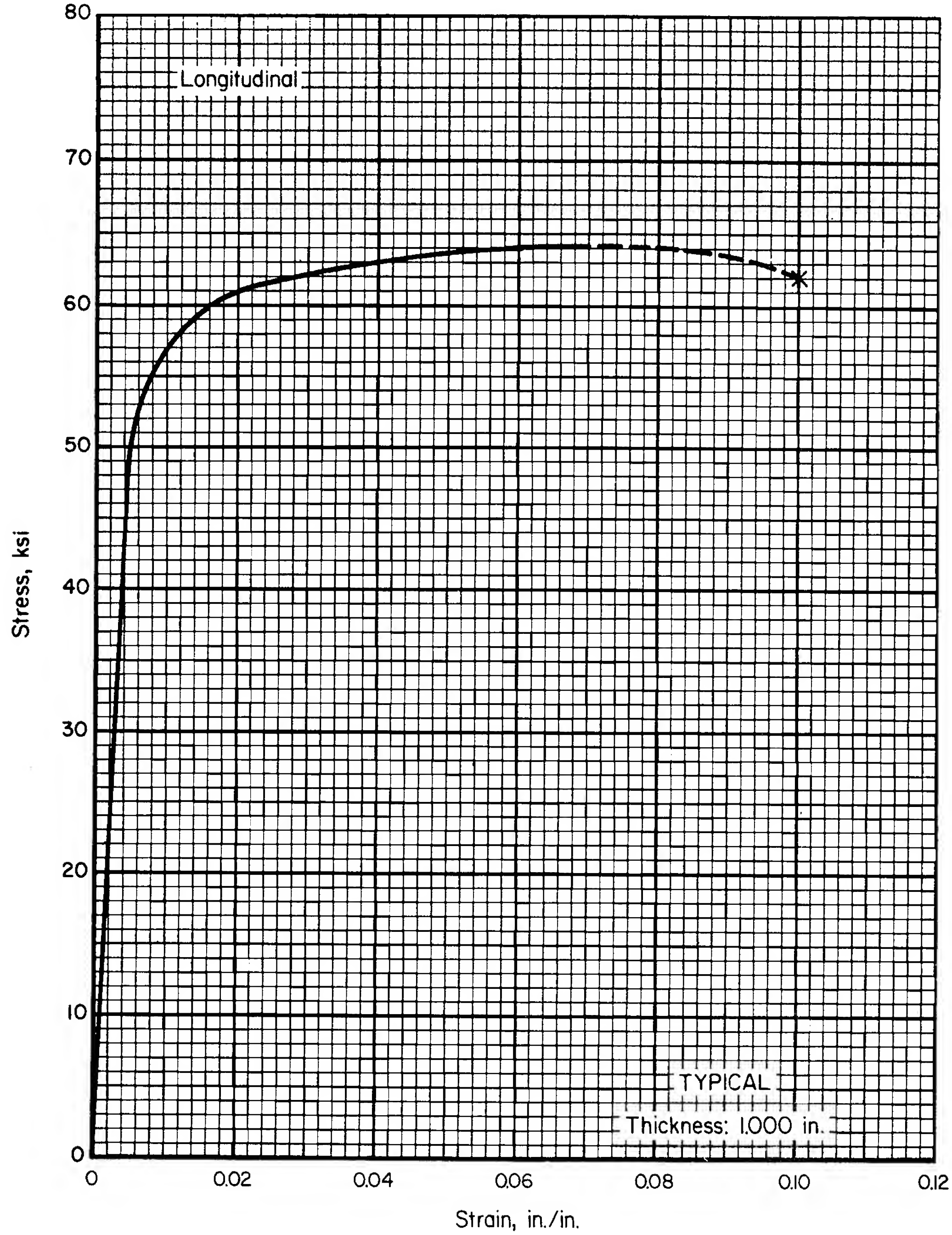

FIGURE 3.2.9.1.6(b). *Typical tensile stress-strain curve (full range) at room temperature for 2618-T61 aluminum alloy forged bar.*

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3.3 3000 Series Wrought Alloys

3.4 4000 Series Wrought Alloys

3.5 5000 Series Wrought Alloys

Alloys of the 5000 series contain magnesium as the principal alloying element and are strengthened by cold work. Because of their high toughness at temperatures down to -452 F, they are widely used in cryogenic applications. Strain-hardened tempers of 5000 series alloys containing more than three percent magnesium should not be used at temperatures above 212 F because susceptibility to stress-corrosion cracking may result.

3.5.1 5052 ALLOY

3.5.1.0 *Comments and Properties.*—5052 is a low-strength Al-Mg alloy but extremely tough at low temperatures as well as at room temperature. It is highly resistant to corrosion; refer to Section 3.1.2.3 for comments regarding the resistance of the alloy to stress-corrosion cracking. Refer to Section 3.1.3.4 for comments regarding the weldability of the alloy.

Material specifications for 5052 aluminum alloy are presented in Table 3.5.1.0(a). Room-temperature mechanical and physical properties are shown in Tables 3.5.1.0(b_1) and (b_2). The effect of temperature on physical properties is shown in Figure 3.5.1.0.

TABLE 3.5.1.0(a). *Material Specifications for 5052 Aluminum Alloy*

Specification	Form
AMS 4015	Sheet and plate
AMS 4016	Sheet and plate
AMS 4017	Sheet and plate
QQ-A-250/8	Sheet and plate

The temper index for 5052 is as follows:

Section	Temper
3.5.1.1	O
3.5.1.2	H32
3.5.1.3	H34
3.5.1.4	H35
3.5.1.5	H38

3.5.1.1 *O-Temper.*—Elevated temperature curves for this temper for various mechanical properties are presented in Figures 3.5.1.1.1, 3.5.1.1.4, and 3.5.1.1.5.

3.5.1.2 *H32 Temper.*—Figure 3.5.1.1.4 may be used for the elevated temperature curve for modulus of elasticity.

3.5.1.3 *H34 Temper.*—Elevated temperature curves for various mechanical properties are presented in Figures 3.5.1.3.1(a) through (d), and 3.5.1.3.5(a) and (b). Use Figure 3.5.1.1.4 for modulus values.

3.5.1.4 *H36 Temper.*—Figure 3.5.1.1.4 may be used for the elevated temperature curve for modulus of elasticity.

3.5.1.5 *H38 Temper.*—Elevated temperature curves for this temper for various mechanical properties are presented in Figures 3.5.1.5.1(a) through (d), and 3.5.1.5.5(a) and (b). Use Figure 3.5.1.1.4 for modulus values.

TABLE 3.5.1.0(b_1). *Design Mechanical and Physical Properties of 5052 Aluminum Alloy Sheet and Plate*

Specification	AMS 4015	AMS 4016	AMS 4017	QQ-A-250/8	
Form	Sheet and plate			Sheet	
Condition	O	H32	H34	H36	H38
Thickness, in.	0.006-3.000	0.017-2.000	0.009-1.000	0.006-0.162	0.006-0.128
Basis	S	S	S	S	S
Mechanical Properties:					
F_{tu}, ksi:					
L	25	31	34	37	39
LT	...	31	34	37	39
F_{ty}, ksi:					
L	9.5	23	26	29[a]	32[a]
LT	...	22	25	29	32
F_{cy}, ksi:					
L	...	22	25	...	...
LT	...	23	26	...	...
F_{su}, ksi	16	19	20	22	23
F_{bru}, ksi:					
(e/D = 1.5)	...	50	54	59	62
(e/D = 2.0)	...	65	71	78	82
F_{bry}, ksi:					
(e/D = 1.5)	...	32	37	41	44
(e/D = 2.0)	...	37	41	46	51
e, percent:					
L	b	b	b	b	b
E, 10^3 ksi	10.1				
E_c, 10^3 ksi	10.2				
G, 10^3 ksi	3.85				
μ	0.33				
Physical Properties:					
ω, lb/in.^{3}	0.097				
C, Btu/(lb)(F)	0.23 (at 212 F)				
K and α	See Figure 3.5.1.0				

[a]From "Aluminum Standards and Data" dated 1982.
[b]See Table 3.5.1.0(b_2).

TABLE 3.5.1.0(b_2). *Minimum Elongation Values for 5052 Aluminum Alloy Sheet and Plate*

Temper	Thickness range, inch	Elongation (L), percent
O	0.006-0.007	...
	0.008-0.012	14
	0.013-0.019	15
	0.020-0.031	16
	0.032-0.050	18
	0.051-0.113	19
	0.114-0.249	20
	0.250-3.000	18
H32	0.017-0.019	4
	0.020-0.050	5
	0.051-0.113	7
	0.114-0.249	9
	0.250-0.499	11
	0.500-2.000	12
H34	0.009-0.019	3
	0.020-0.050	4
	0.051-0.113	6
	0.114-0.249	7
	0.250-1.000	10
H36	0.006-0.007	2
	0.008-0.031	3
	0.032-0.162	4
H38	0.006-0.007	2
	0.008-0.031	3
	0.032-0.128	4

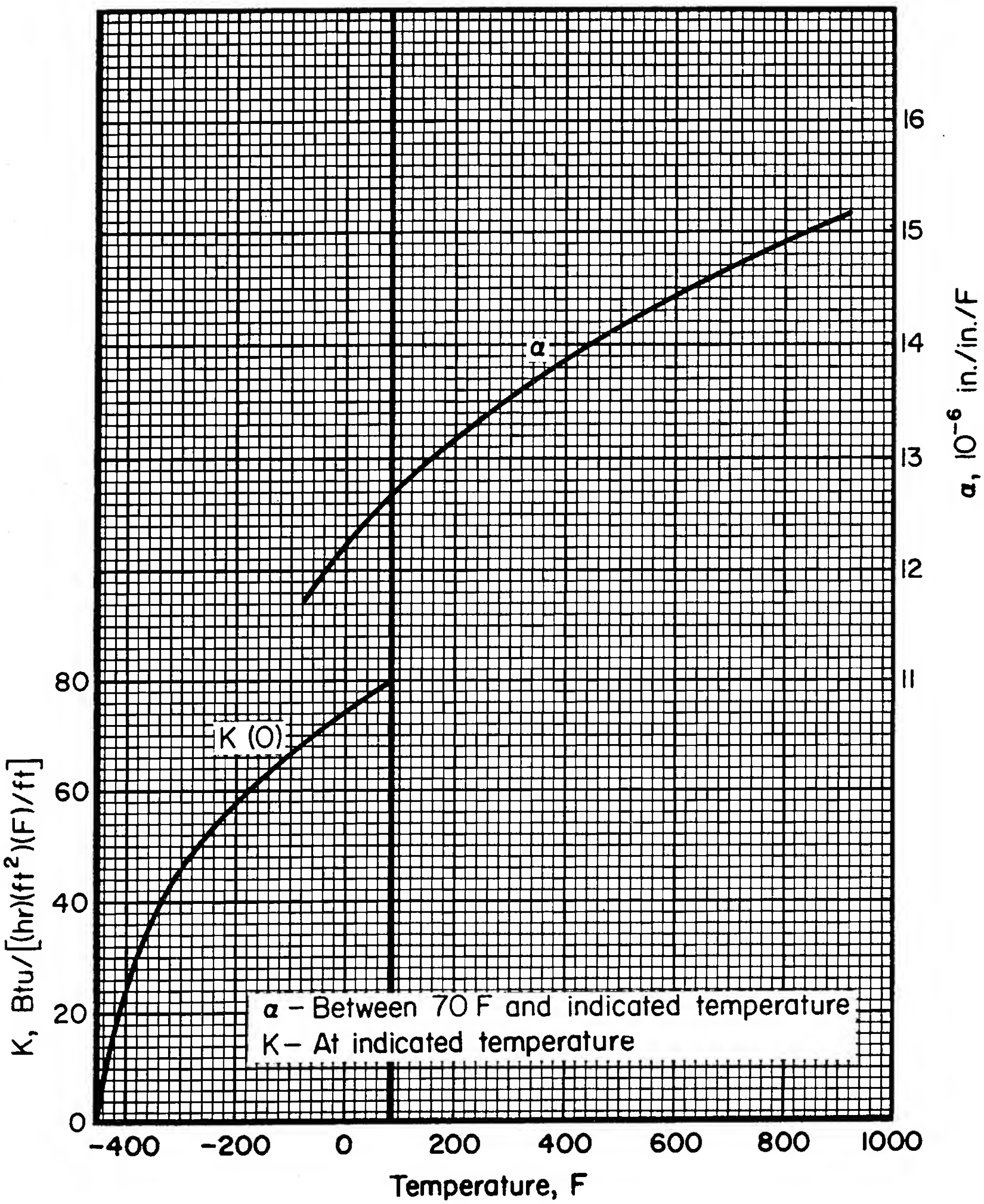

FIGURE 3.5.1.0. *Effect of temperature on the physical properties of 5052 aluminum alloy.*

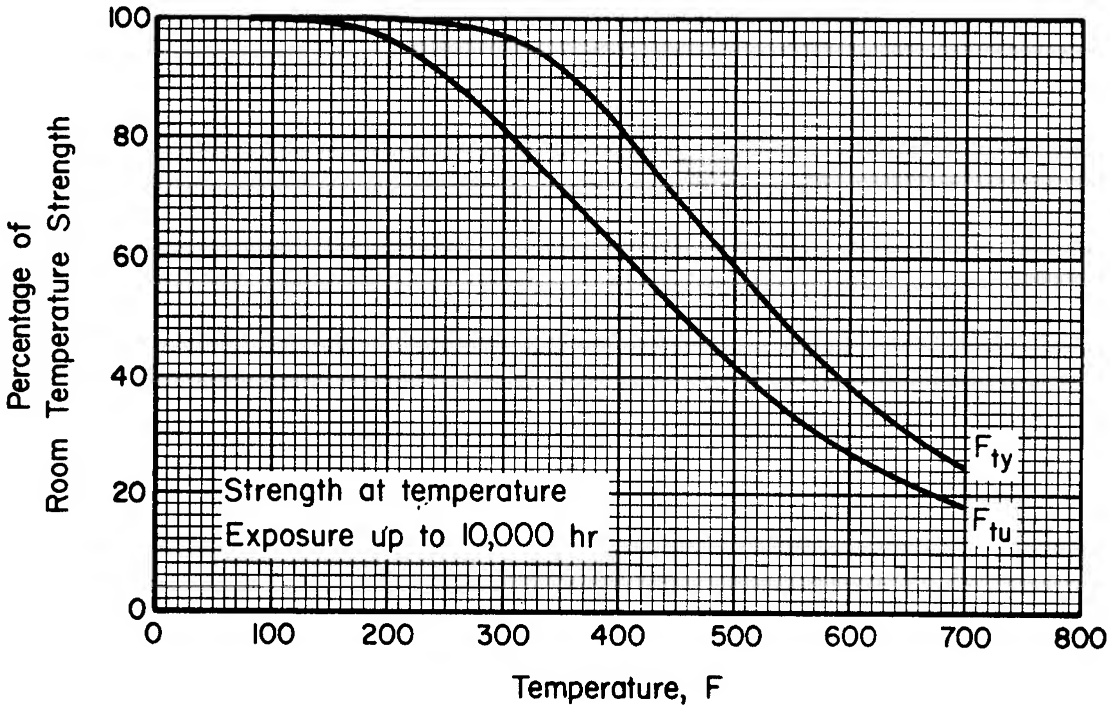

FIGURE 3.5.1.1.1. *Effect of temperature on the tensile ultimate strength (F_{tu})and the tensile yield strength (F_{ty}) of 5052-0 aluminum alloy (all products).*

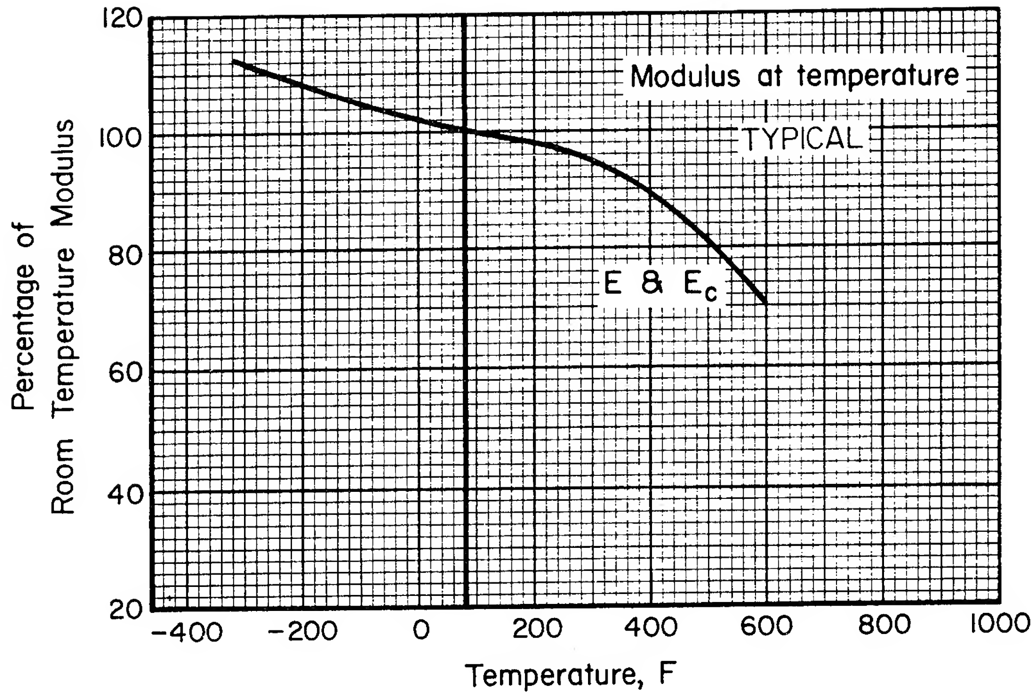

FIGURE 3.5.1.1.4. *Effect of temperature on the tensile and compressive module (E and E_c) of 5052-0 aluminum alloy (all products).*

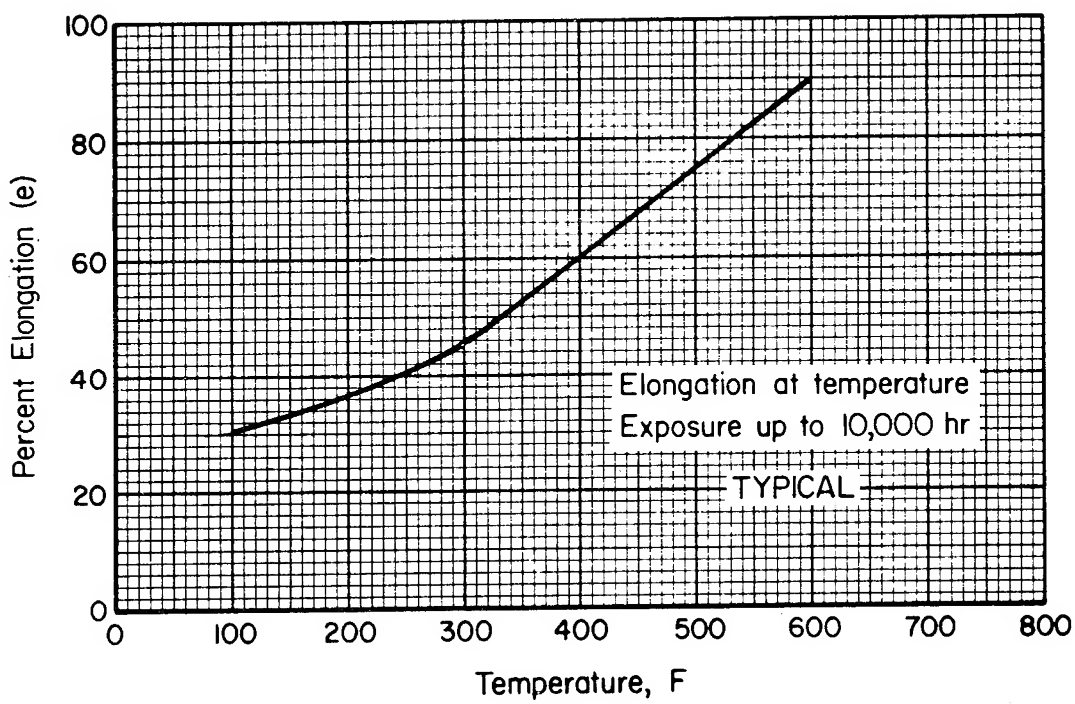

FIGURE 3.5.1.1.5. *Effect of temperature on the elongation of 5052-0 aluminum alloy (all products).*

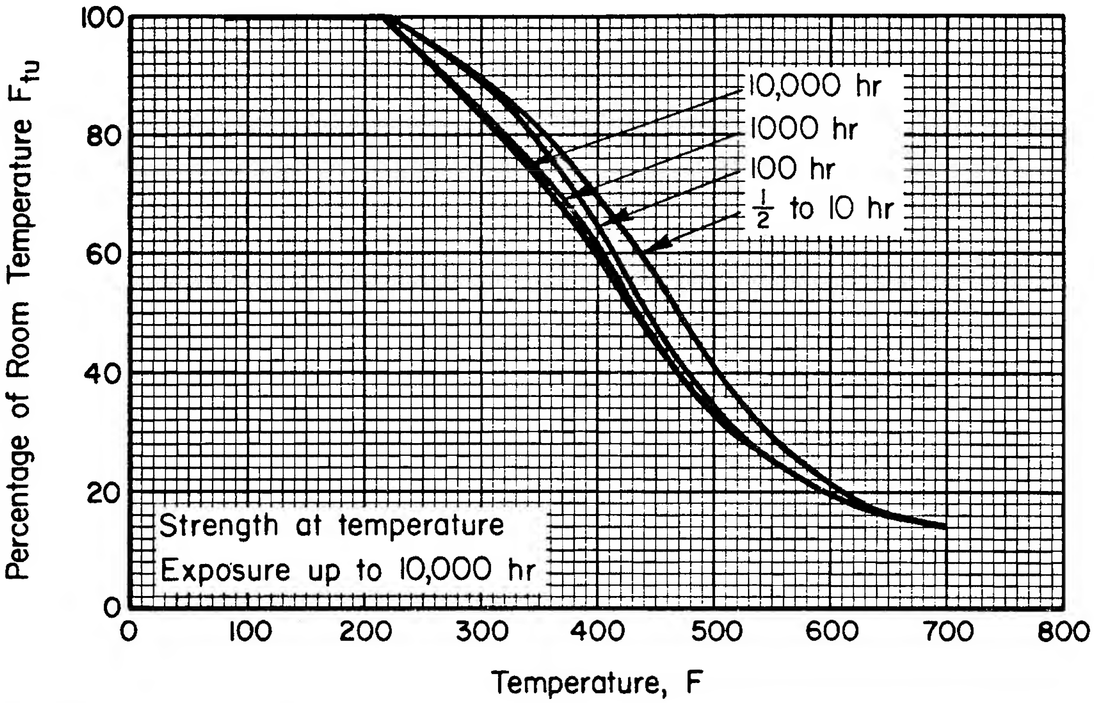

FIGURE 3.5.1.3.1(a). *Effect of temperature on the tensile ultimate strength (F_{tu}) of 5052-H34 aluminum alloy sheet and plate.*

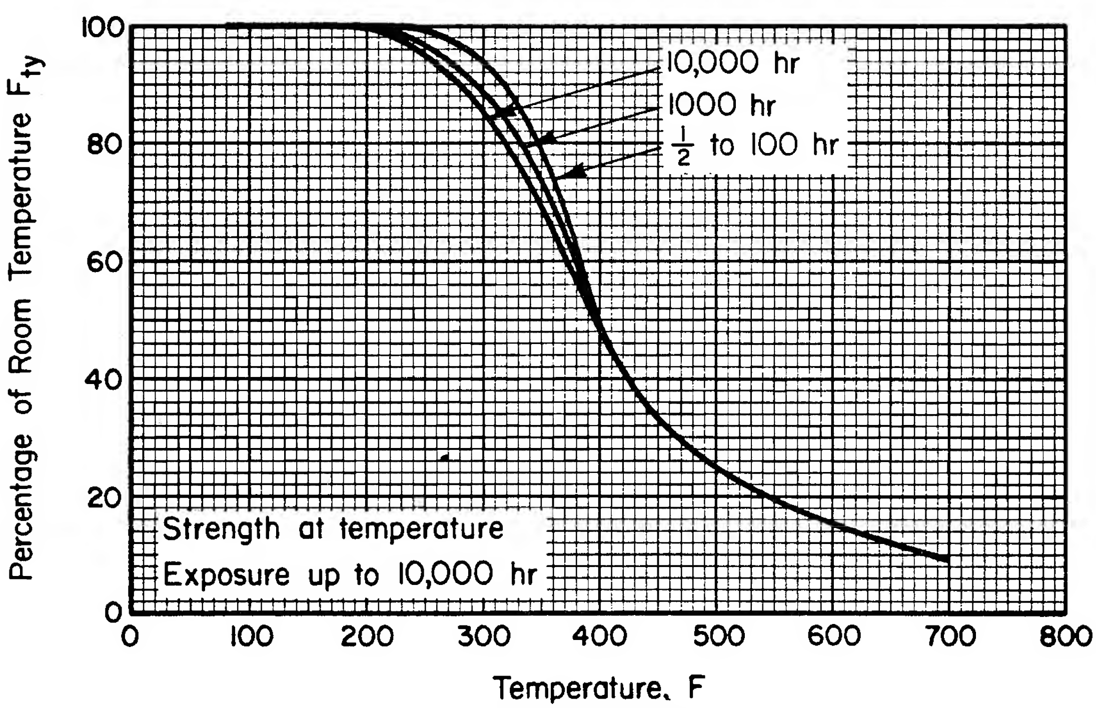

FIGURE 3.5.1.3.1(b). *Effect of temperature on the tensile yield strength (F_{ty}) of 5052-H34 aluminum alloy sheet and plate.*

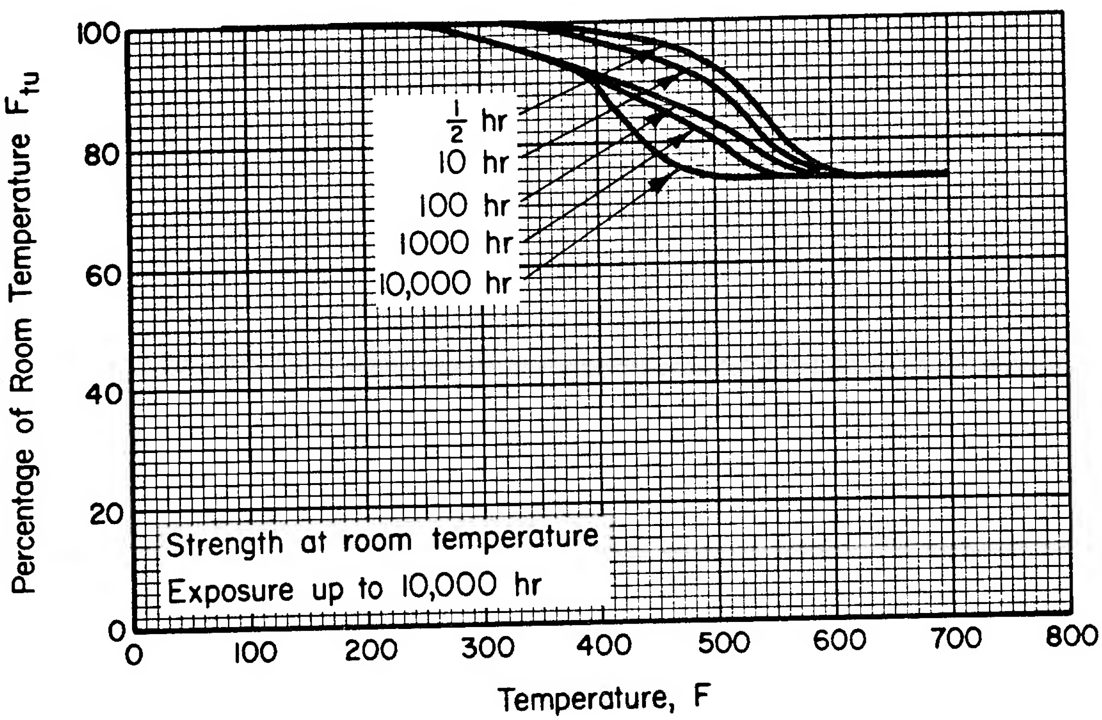

FIGURE 3.5.1.3.1(c). *Effect of exposure at elevated temperatures on the room-temperature tensile ultimate strength (F_{tu}) of 5052-H34 aluminum alloy sheet and plate.*

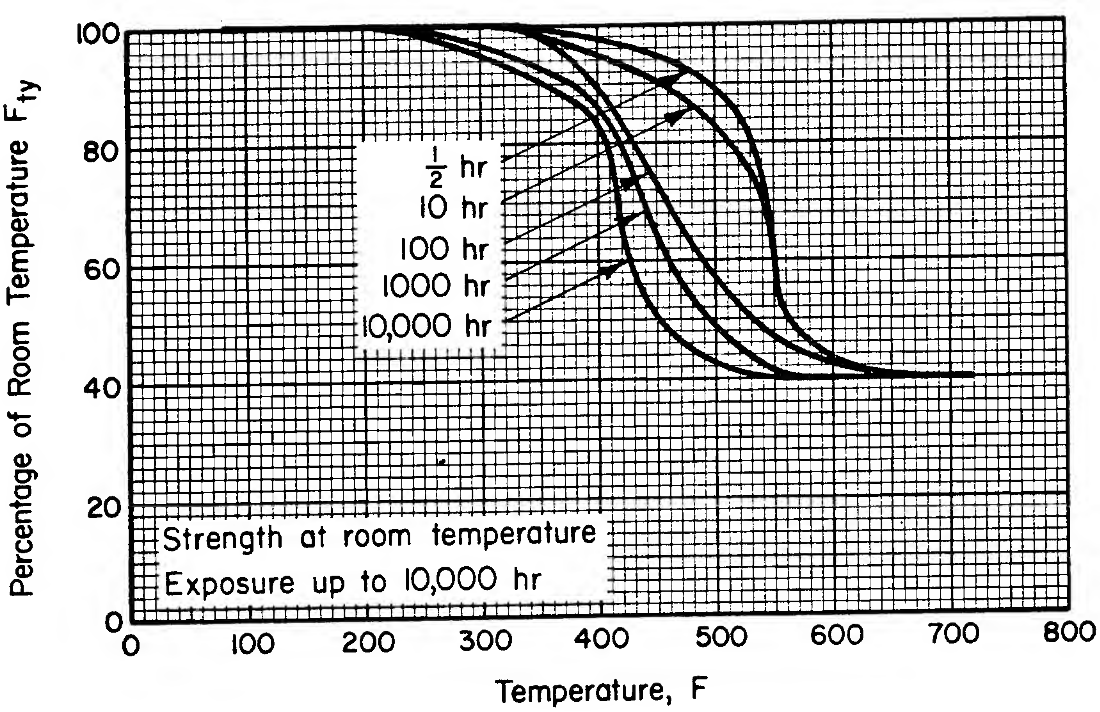

FIGURE 3.5.1.3.1(d). *Effect of exposure at elevated temperatures on the room-temperature tensile yield strength (F_{ty}) of 5052-H34 aluminum alloy sheet and plate.*

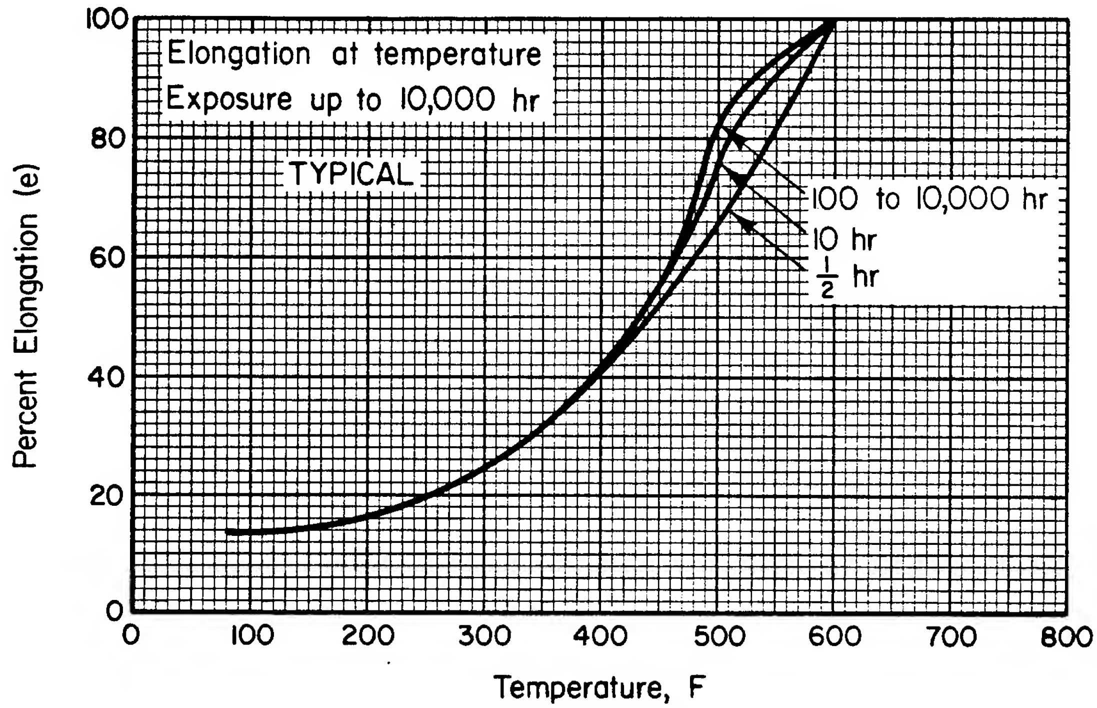

FIGURE 3.5.1.3.5(a). *Effect of temperature on the elongation (e) of 5052-H34 aluminum alloy sheet and plate.*

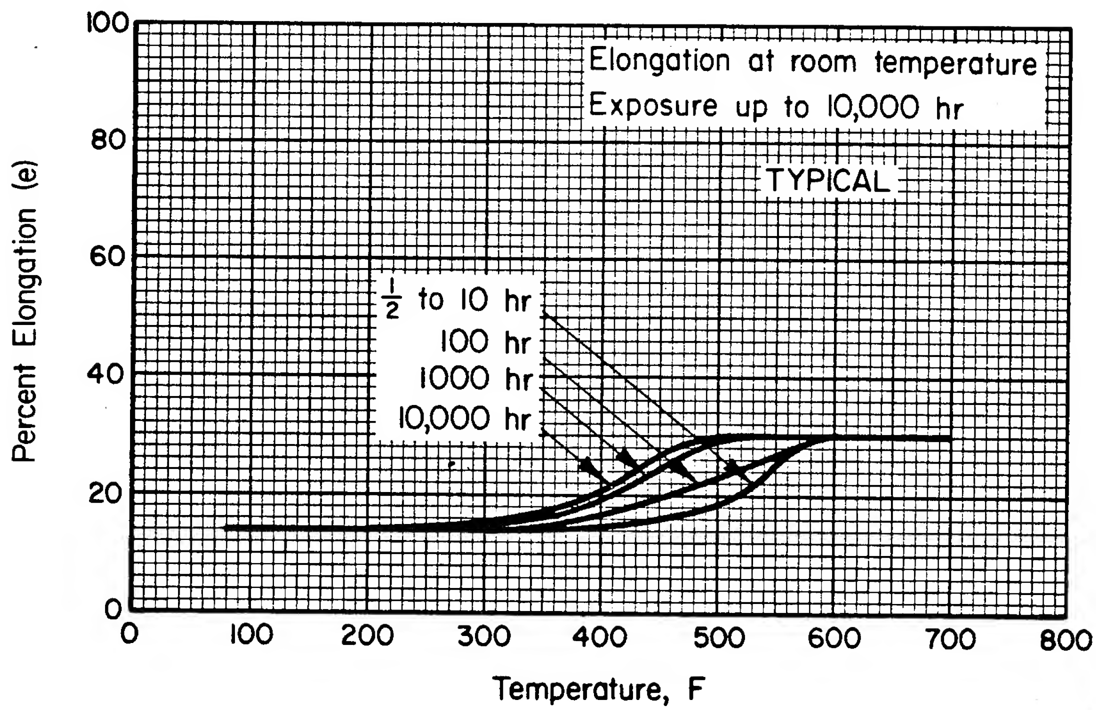

FIGURE 3.5.1.3.5(b). *Effect of exposure at elevated temperatures on the elongation (e) of 5052-H34 aluminum alloy sheet and plate.*

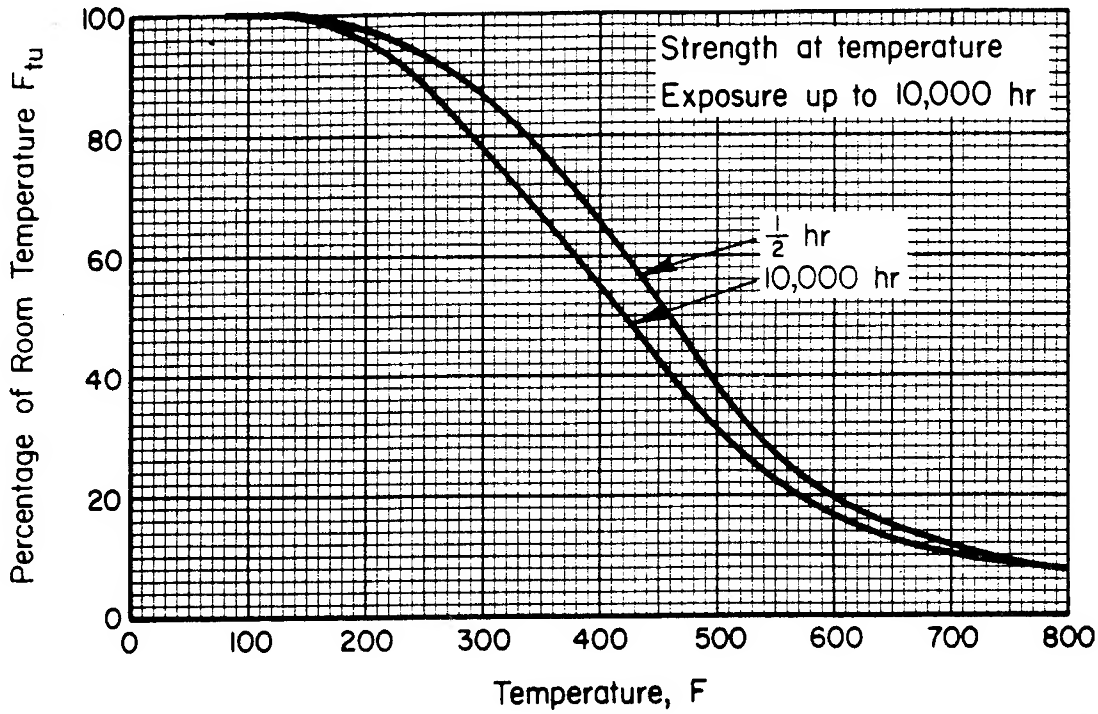

FIGURE 3.5.1.5.1(a). *Effect of temperature on the tensile ultimate strength (F_{tu}) of 5052-H38 aluminum alloy (all products.)*

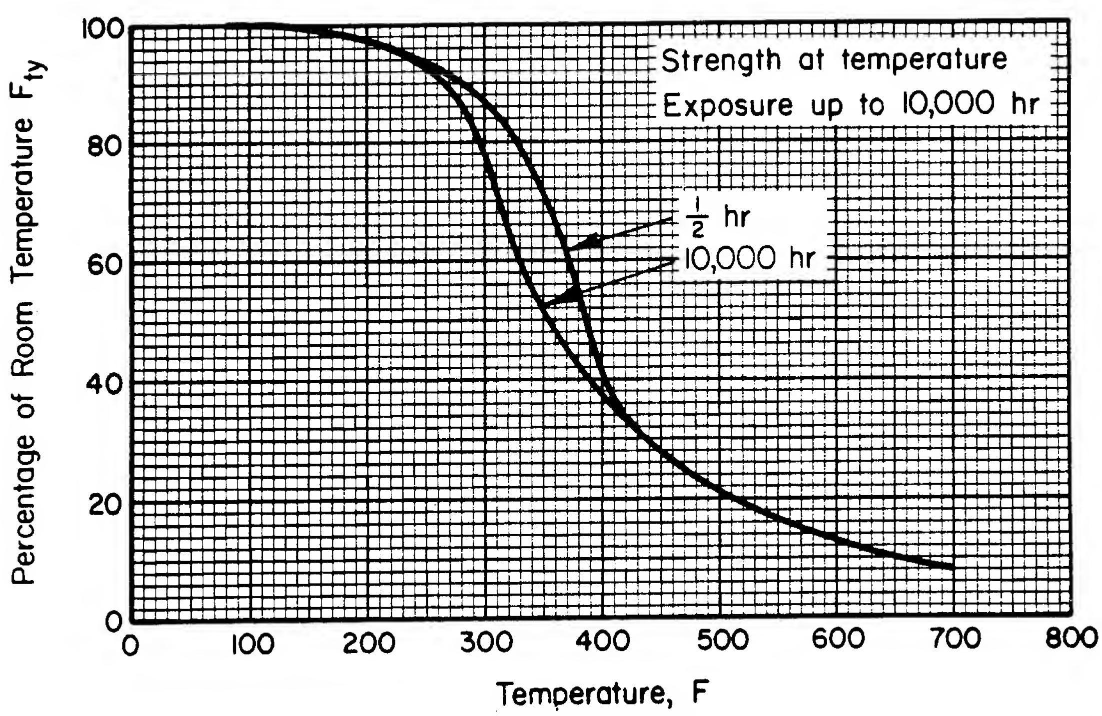

FIGURE 3.5.1.5.1(b). *Effect of temperature on the tensile yield strength (F_{ty}) of 5052-H38 aluminum alloy (all products).*

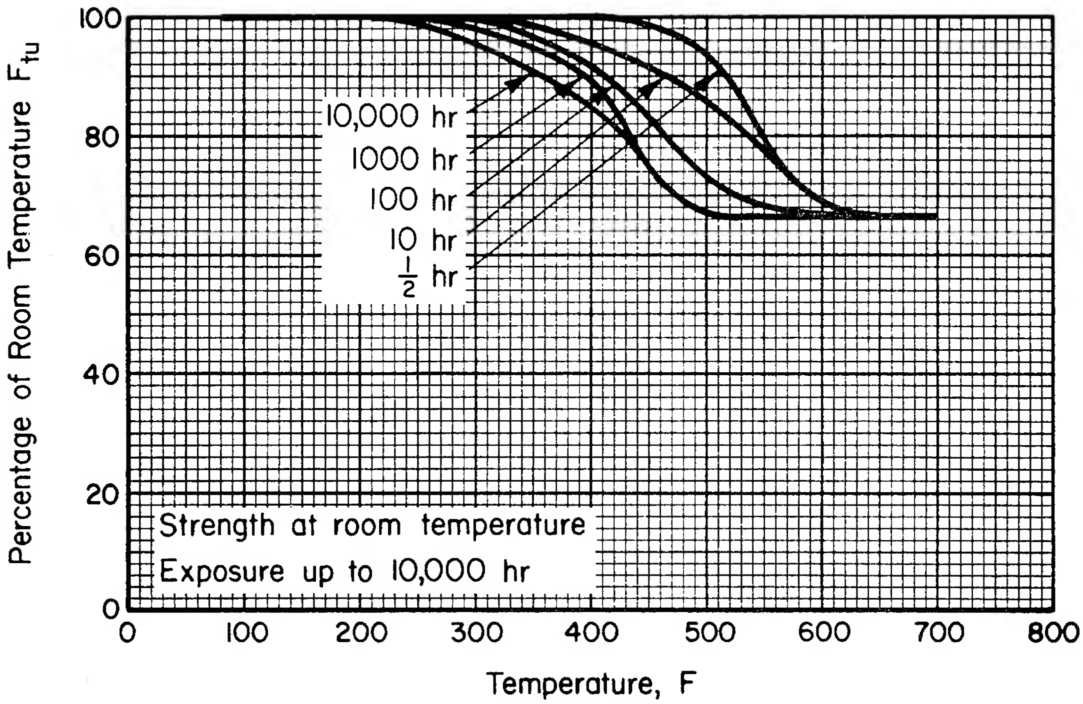

FIGURE 3.5.1.5.1(c). *Effect of exposure at elevated temperatures on the room-temperature tensile ultimate strength (F_{tu}) of 5052-H38 aluminum alloy (all products).*

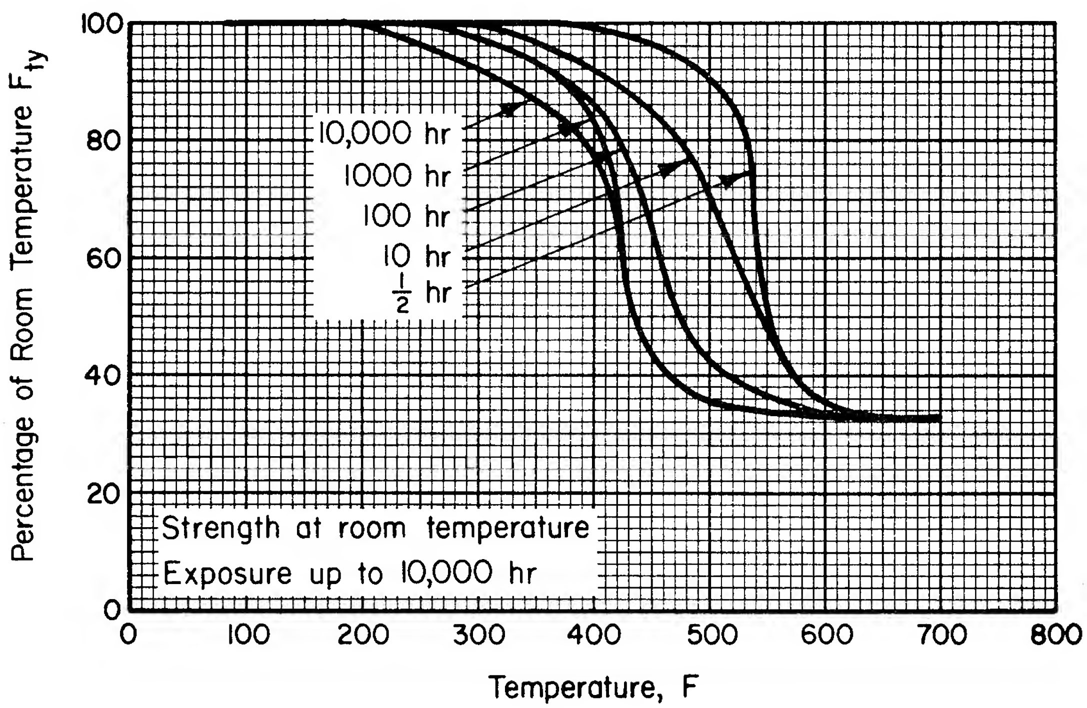

FIGURE 3.5.1.5.1(d). *Effect of exposure at elevated temperatures on the room-temperature tensile yield strength (F_{ty}) of 5052-H38 aluminum alloy (all products).*

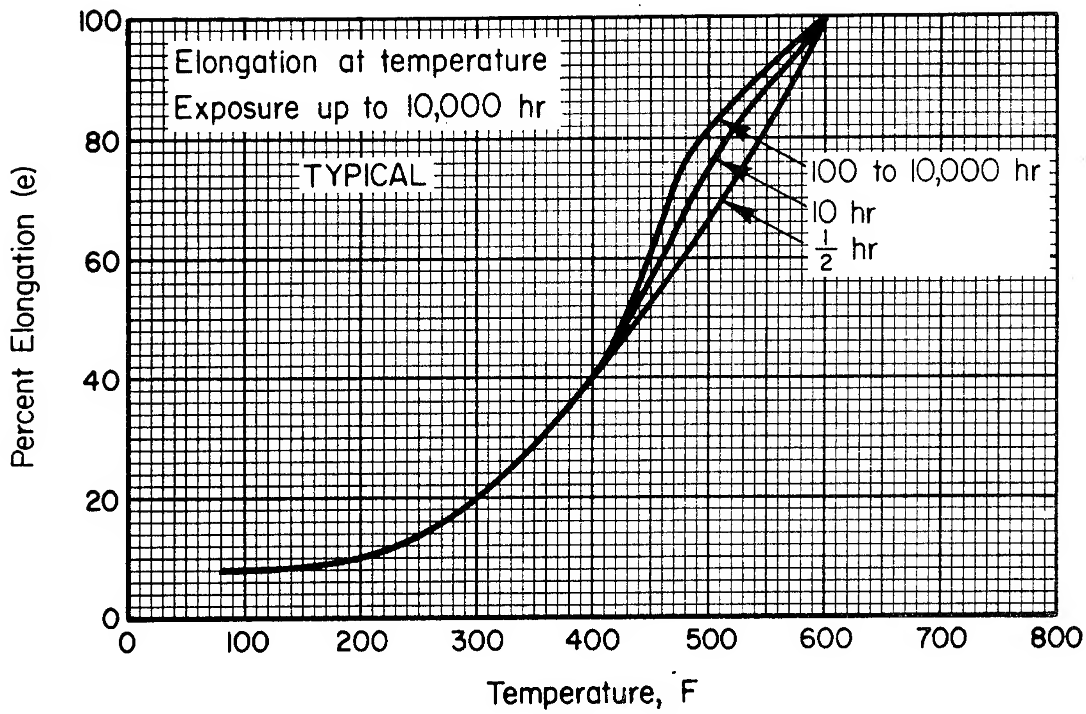

FIGURE 3.5.1.5.5(a). *Effect of temperature on the elongation of 5052-H38 aluminum alloy (all products).*

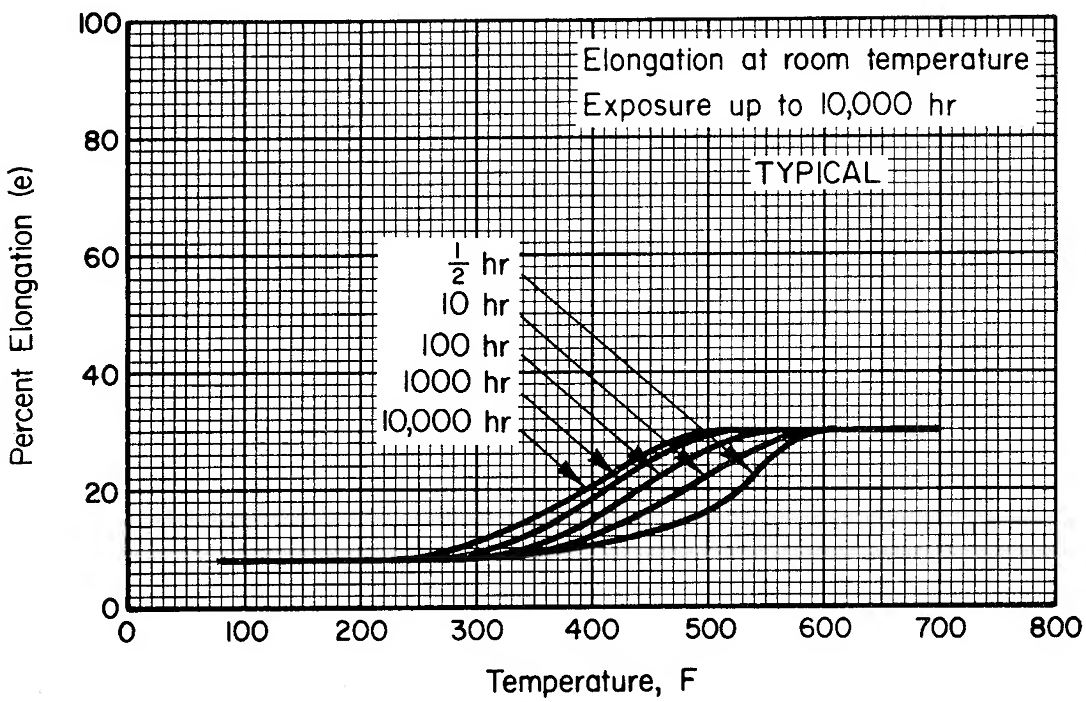

FIGURE 3.5.1.5.5(b). *Effect of exposure at elevated temperatures on the elongation of 5052-H38 aluminum alloy (all products).*

3.5.2 5083 ALLOY

3.5.2.0 *Comments and Properties.*—5083 is a high-strength Al-Mg alloy which has been widely used in cryogenic applications, because of its excellent combination of strength and toughness. It has high resistance to corrosion, but strain-hardened tempers should not be used at temperature because of possible sensitization to stress-corrosion cracking. Refer to Section 3.1.2.3 for comments regarding the resistance of the alloy to stress-corrosion cracking, and to Section 3.1.3.4 for comments regarding the weldability of the alloy.

Material specifications for 5083 aluminum alloy are presented in Table 3.5.2.0(a). Room-temperature mechanical and physical properties are shown in Tables 3.5.2.0(b) and (c). The effect of temperature on thermal expansion is shown in Figure 3.5.2.0.

TABLE 3.5.2.0(a). *Material Specifications for 5083 Aluminum Alloy*

Specification	Form
AMS 4056	Bare sheet and plate
QQ-A-250/6	Bare sheet and plate
QQ-A-200/4	Extruded bar, rod, and shapes

The temper index for 5083 is as follows:

Section	Temper
3.5.2.1	O
3.5.2.2	H1111
3.5.2.3	H112
3.5.2.4	H321
3.5.2.5	H323
3.5.2.6	H343

3.5.2.1 *O Temper.*—Tensile and compressive stress-strain and tangent-modulus curves at room temperature are presented in Figures 3.5.2.1.6(a) and (b). A full-range tensile stress-strain curve is shown in Figure 3.5.2.1.6(c) at room temperature.

TABLE 3.5.2.0(b). *Design Mechanical and Physical Properties of 5083 Aluminum Alloy Sheet and Plate*

Specification	AMS 4056 and QQ-A-250/6							QQ-A-250/6									
Form	Sheet and plate																
Temper	O							H112		H321			H323			H343	
Thickness, in.	0.051-1.500		1.501-3.000	3.001-4.000	4.001-5.000	5.001-7.000	7.001-8.000	0.250-1.500	1.501-3.000	0.188-1.500		1.501-3.000	0.051-0.125		0.126-0.249	0.051-0.125	0.126-0.249
Basis	A	B	S	S	S	S	S	S	S	A	B	S	A	B	S	S	S
Mechanical Properties:																	
F_{tu}, ksi:																	
L	40	41	39	38	38	37	36	40	39	44	46	41	45	47	45	50	50
LT	40	41	...	...	...	...	...	...	...	44	46	...	...	...	...	...	...
F_{ty}, ksi:																	
L	18	19	17	16	16	15	14	18	17	31	32	29	34	36	34	39	39
LT	18	19	...	...	...	...	...	...	...	28	28	...	...	...	...	...	...
F_{cy}, ksi:																	
L	18	19	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...
LT	18	19	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...
F_{su}, ksi	25	26	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...
F_{bru}, ksi:																	
(e/D = 1.5)	60	62	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...
(e/D = 2.0)	76	78	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...
F_{bry}, ksi:																	
(e/D = 1.5)	32	34	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...
(e/D = 2.0)	38	40	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...
e, percent (S basis):																	
L	16	...	16	16	14	14	12	12	12	12	...	12	8	...	10	6	8
E, 10^3 ksi	10.2																
E_c, 10^3 ksi	10.4																
G, 10^3 ksi	3.85																
μ	0.33																
Physical Properties:																	
ω, lb/in.^{3}	0.096																
C, Btu/(lb)(F)	0.23 (at 212 F)																
K, Btu/[(hr)(ft^2)(F)/ft]	68 (at 77 F)																
α, 10^{-6} in./in./F	See Figure 3.5.2.0																

TABLE 3.5.2.0(c). *Design Mechanical and Physical Properties of 5083 Aluminum Alloy Extrusion*

Specification	QQ-A-200/4			
Form	Extrusion			
Temper	O	H111		H112
Thickness, in.	≤5.000[a]	<0.500[a]	0.501-5.000[a]	≤5.000[a]
Basis	S	S	S	S
Mechanical Properties:				
F_{tu}, ksi:				
L	39	40	40	39
LT	...	40	32	...
F_{ty}, ksi:				
L	16	24	24	16
LT	...	24	19	...
F_{cy}, ksi:				
L	...	...	...	...
LT	...	...	...	...
F_{su}, ksi	...	...	...	...
F_{bru}, ksi:				
(e/D = 1.5)	...	...	...	...
(e/D = 2.0)	...	...	...	...
F_{bry}, ksi:				
(e/D = 1.5)	...	....	...	...
(e/D = 2.0)	...	...	...	...
e, percent:				
L	14	12	12	12
E, 10^3 ksi	10.2			
E_c, 10^3 ksi	10.4			
G, 10^3 ksi	3.35			
μ	0.33			
Physical Properties:				
ω, lb/in.^{3}	0.096			
C, Btu/(lb)(F)	0.23 (at 212 F)			
K, Btu/[(hr)(ft^2)(F)/ft]	68 (at 77 F)			
α, 10^{-6} in./in./F	See Figure 3.5.2.0			

[a]Cross-sectional area ≤ 32.

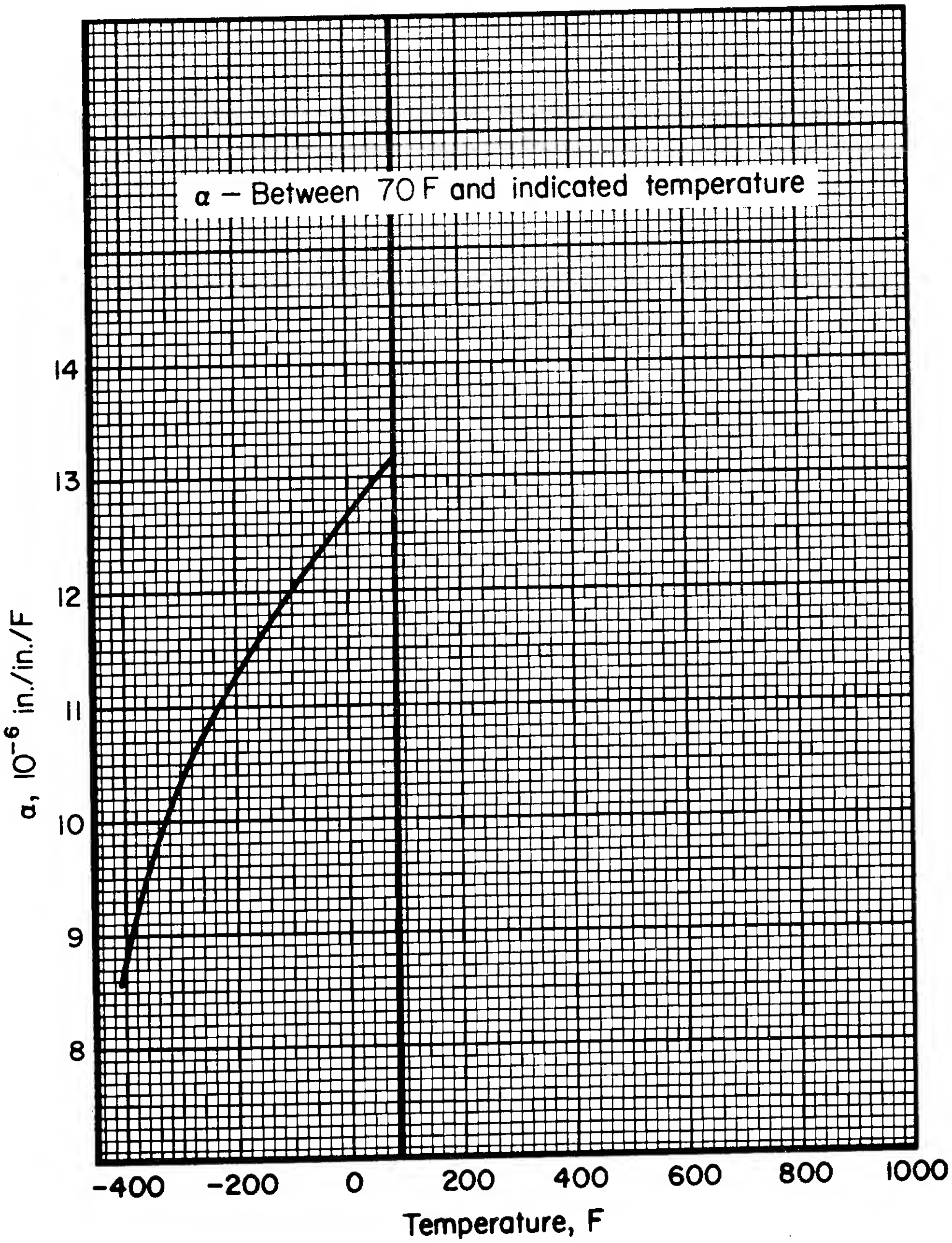

FIGURE 3.5.2.0. *Effect of temperature on the thermal expansion of 5083 aluminum alloy.*

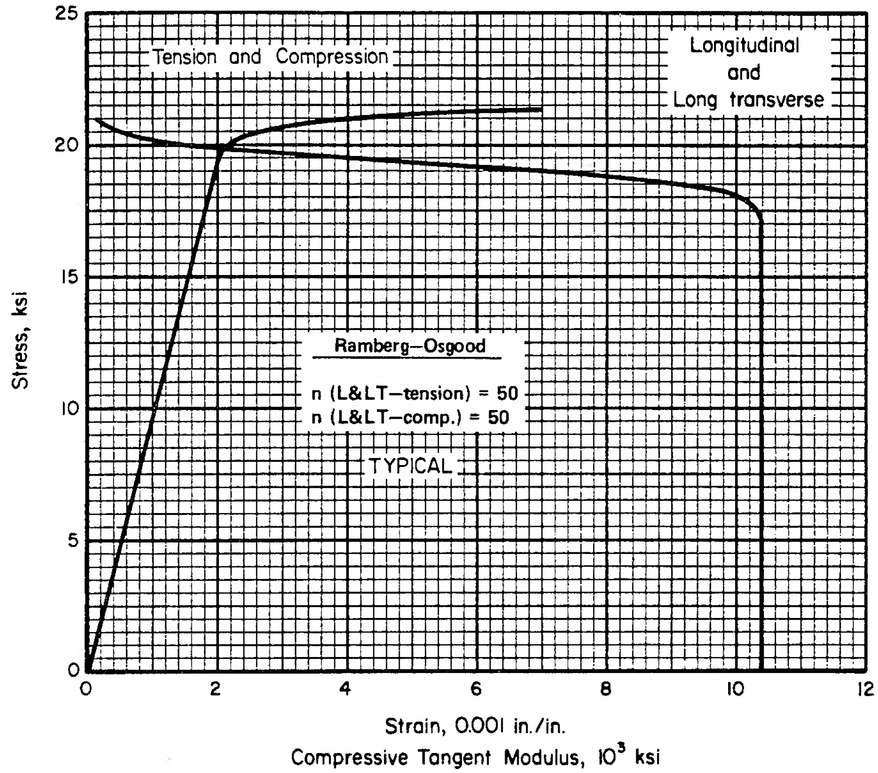

FIGURE 3.5.2.1.6(a). *Typical tensile and compressive stress-strain and compressive tangent-modulus curves for 5083-0 aluminum alloy sheet at room temperature.*

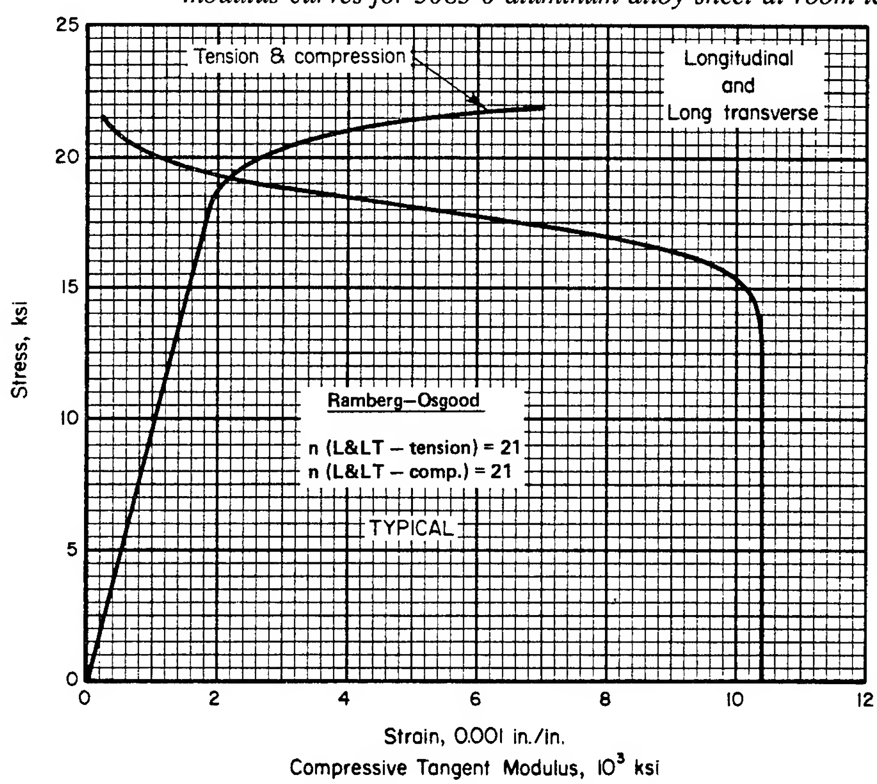

FIGURE 3.5.2.1.6(b). *Typical tensile and compressive stress-strain and compressive tangent-modulus curves for 5083-0 aluminum alloy plate at room temperature.*

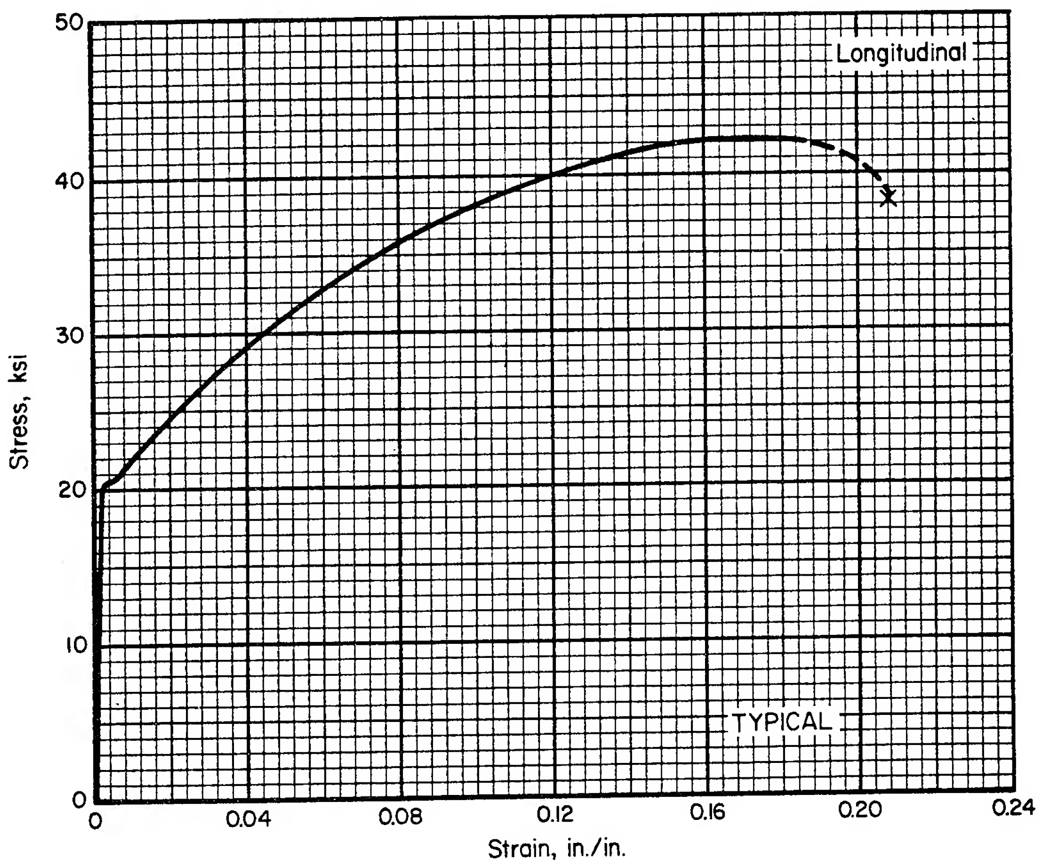

FIGURE 3.5.2.1.6(c). *Typical tensile stress-strain curve (full range) for 5083-O aluminum alloy plate at room temperature.*

3.5.3 5086 ALLOY

3.5.3.0 *Comments and Properties.*—5086 is a tough, medium-strength Al-Mg alloy suitable for application over the range of temperatures from -452 to 212 F. Refer to Section 3.1.2.3 for comments regarding resistance of the alloy to stress-corrosion cracking, and to Section 3.1.3.4 for comments regarding the weldability of the alloy.

Material specifications for 5086 aluminum alloy are presented in Table 3.5.3.0(a). Room-temperature mechanical and physical properties are shown in Tables 3.5.3.0(b) and (c).

TABLE 3.5.3.0(a). *Material Specifications for 5086 Aluminum Alloy*

Specification	Form
QQ-A-250/7	Sheet and plate
QQ-A-200/5	Extruded bar, rod, and shapes

The temper index for 5086 is as follows:

Section	Temper
3.5.3.1	O
3.5.3.2	H32
3.5.3.3	H34
3.5.3.4	H36
3.5.3.5	H38
3.5.3.6	H111
3.5.3.7	H112

3.5.3.1 *O Temper.*—Tensile, compressive stress-strain and tangent modulus curves at room temperature are shown in Figures 3.5.3.1.6(a) and (b) for products with this temper. Figure 3.5.3.1.6(c) is a full-range tensile stress-strain curve.

3.5.3.2 *H32 Temper.*—Figures 3.5.3.2.6(a) and (b) show tensile and compressive stress-strain and tangent-modulus curves at room temperature.

3.5.3.3 *H34 Temper.*—Figures 3.5.3.3.6(a) and (b) show tensile, compressive stress-strain, and tangent-modulus curves for this temper. A full-range tensile stress-strain curve is shown in Figure 3.5.3.3.6(c).

3.5.3.4 *H36 Temper.*—Figure 3.5.3.4.6 shows tensile, compressive stress-strain and tangent-modulus curves at room temperature.

3.5.3.5 *H38 Temper.*

3.5.3.6 *H111 Temper.*

3.5.3.7 *H112 Temper.*—Figure 3.5.3.7.6 shows tensile, compressive stress-strain and tangent-modulus curves at room temperature.

TABLE 3.5.3.0(b). *Design Mechanical and Physical Properties of 5086 Aluminum Alloy Sheet, Plate and Extrusion*

Specification	QQ-A-250/7											QQ-A-200/5		
Form	Sheet and plate											Extrusion		
Temper	O		H32		H34	H36	H38	H112				O	H111	H1112
Thickness, in.	0.020-2.000		0.020-2.000		0.009-1.000	0.006-0.162	0.006-0.020	0.188-0.499	0.500-1.000	1.001-2.000	2.001-3.000	≤ 5.000[a]	≤ 5.000[a]	≤ 5.000[a]
Basis	A	B	A	B	S	S	S	S	S	S	S	S	S	S
Mechanical properties:														
F_{tu}, ksi:														
L	35	36	40	41	44	47	50	36	35	35	34	35	36	35
LT	35	36	40	41	44	47	...	36	35	35	34	...	...	...
F_{ty}, ksi:														
L	14	15	28	30	34	38	41	18	16	14	14	14	21	14
LT	14	15	26	28	33	37	...	17	16	14	14	...	...	...
F_{cy}, ksi:														
L	14	15	26	28	32	35	...	17	15	14	14	...	...	...
LT	14	15	28	30	34	38	...	18	16	14	14	...	...	...
F_{su}, ksi	21	22	24	25	26	27	...	22	21	21	20	...	...	...
F_{bru}, ksi:														
(e/D=1.5)	52	53	58	61	64	68	...	54	52	52	51	...	...	...
(e/D=2.0)	70	72	80	82	88	94	...	72	70	70	68	...	...	...
F_{bry}, ksi:														
(e/D=1.5)	24	26	39	42	48	53	...	25	24	24	24	...	...	...
(e/D=2.0)	28	30	48	51	58	65	...	31	28	28	28	...	...	...
e, percent (S-basis):														
L	b	...	b	...	b	b	3	8	10	14	14	14	12	12
E, 10^3 ksi	10.2													
E_c, 10^3 ksi	10.4													
G, 10^3 ksi	3.85													
μ	0.33													
Physical properties:														
ω, lb/in.^{3}	0.096													
C, Btu/(lb)(F)	0.23 (at 212 F)													
K, Btu/[(hr)(ft^2)(F)/ft]	72 (at 77 F)													
α, 10^{-6}in./in./F	13.2 (68 to 212 F)													

[a]Cross-sectional area ≤ 32.
[b]See Table 3.5.3.0(c).

TABLE 3.5.3.0(c). *Minimum Elongation Values for 5086 Aluminum Alloy Sheet and Plate*

Temper	Thickness range, inch	Elongation (L), percent
O	0.020-0.050	15
	0.051-0.249	18
	0.250-2.000	16
H32	0.020-0.050	6
	0.051-0.249	8
	0.250-2.000	12
H34	0.009-0.019	4
	0.020-0.050	5
	0.051-0.249	6
	0.250-1.000	10
H36	0.006-0.019	3
	0.020-0.050	4
	0.051-0.162	6

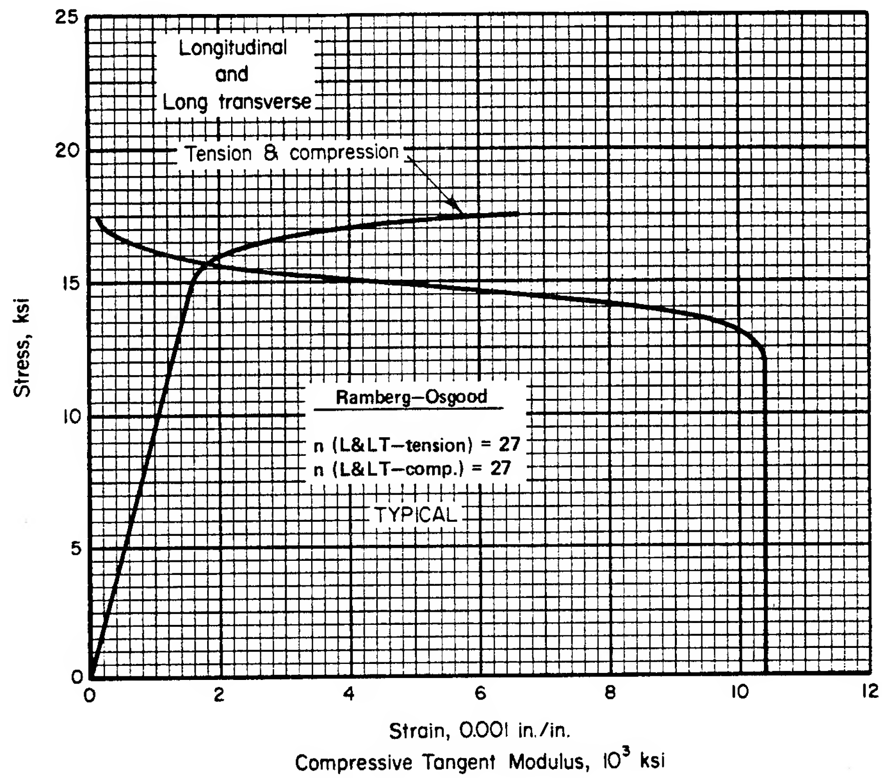

FIGURE 3.5.3.1.6(a). *Typical tensile and compressive stress-strain and compressive tangent-modulus curves for 5086-0 aluminum alloy sheet at room temperature.*

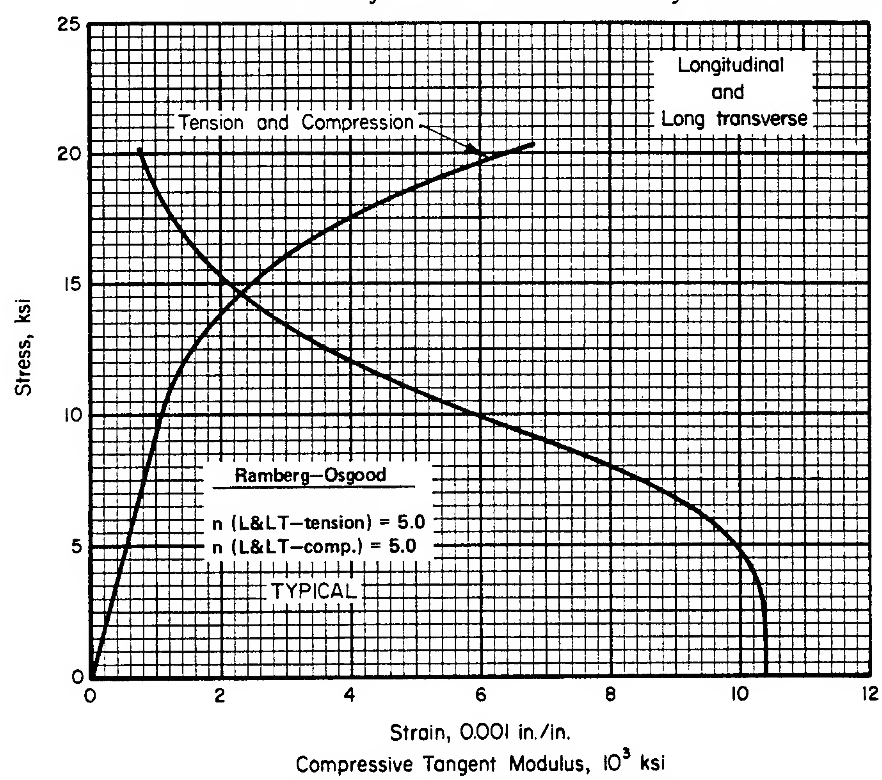

FIGURE 3.5.3.1.6(b). *Typical tensile and compressive stress-strain and compressive tangent-modulus curves for 5086-0 aluminum alloy plate and extrusion at room temperature.*

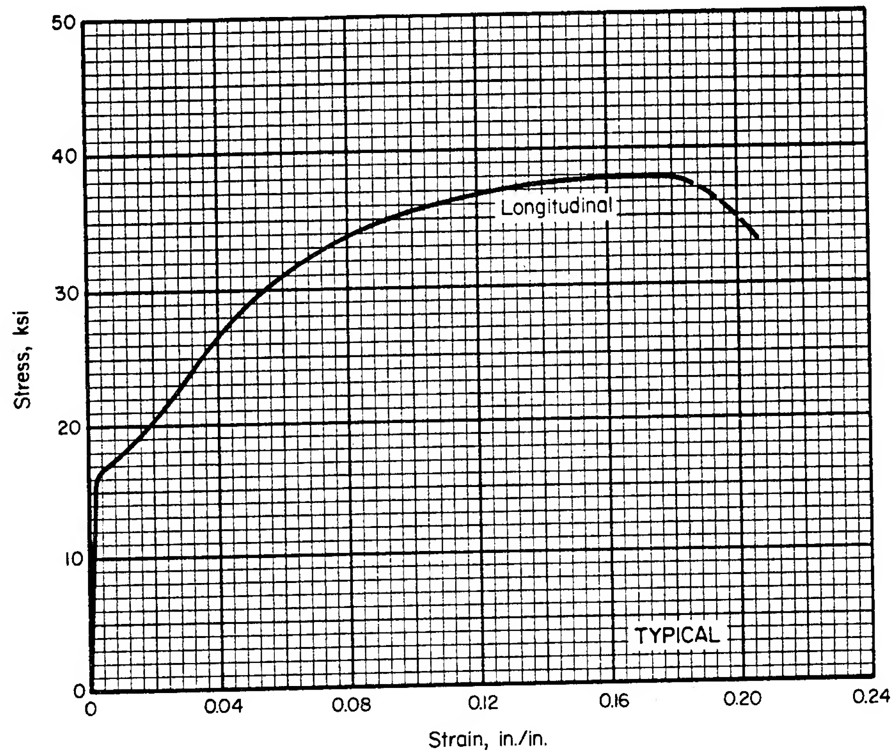

FIGURE 3.5.3.1.6(c). *Typical tensile stress-strain curve (full range) for 5086-0 aluminum alloy sheet at room temperature.*

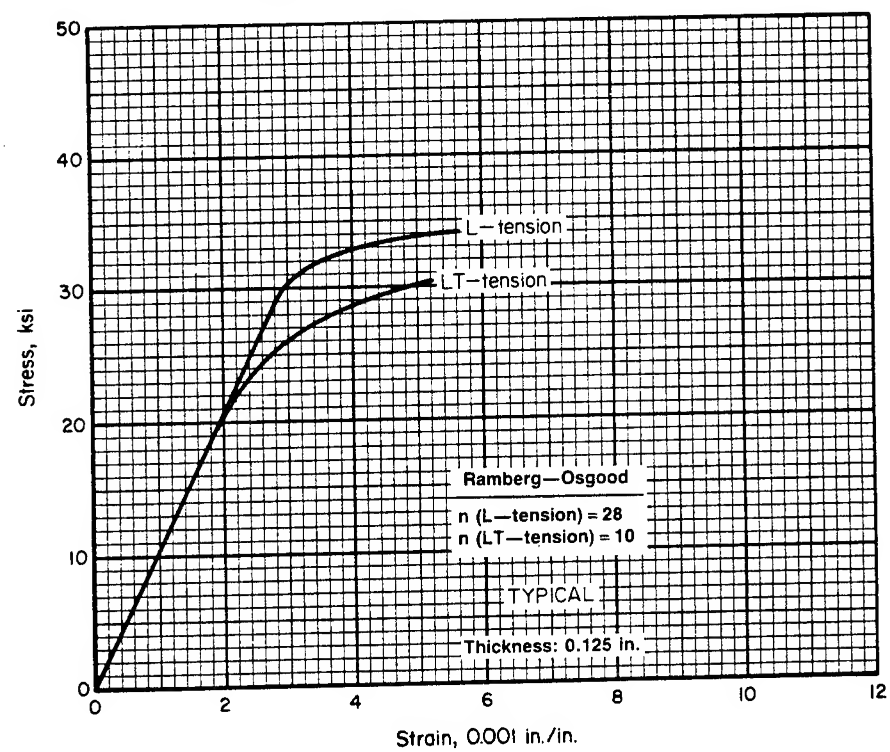

FIGURE 3.5.3.2.6(a). *Typical tensile stress-strain curves for 5086-H32 aluminum alloy sheet at room temperature.*

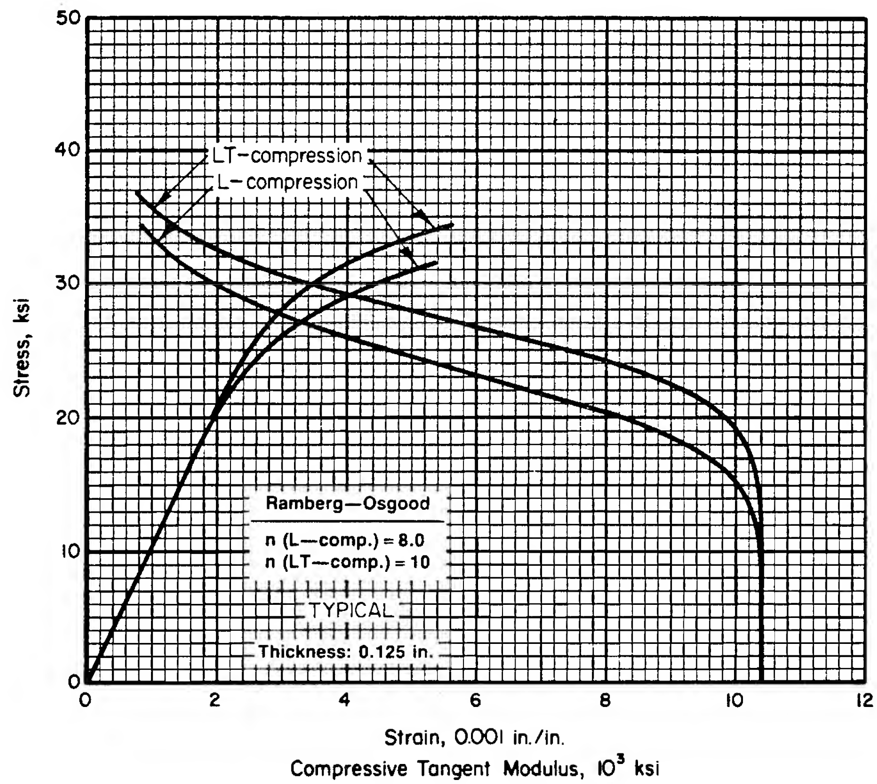

FIGURE 3.4.3.2.6(b). *Typical compressive stress-strain and compressive tangent-modulus curves for 5086-H32 aluminum alloy sheet at room temperature.*

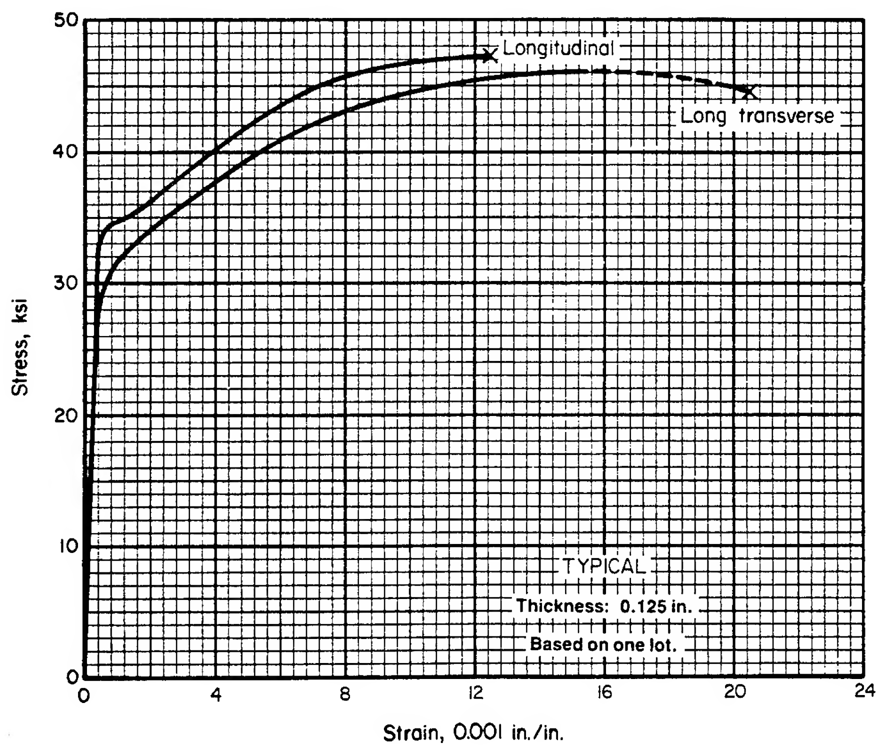

FIGURE 3.4.3.2.6(c). *Typical tensile stress-strain curves (full-range) for 5086-H32 aluminum alloy sheet at room temperature.*

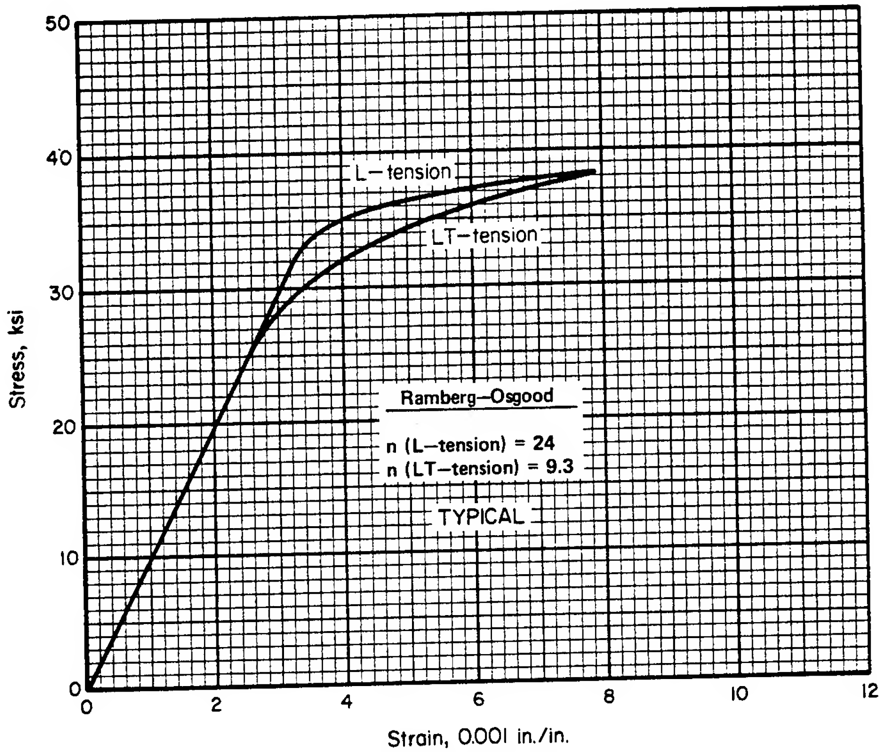

FIGURE 3.5.3.3.6(a). *Typical tensile stress-strain curves for 5086-H34 aluminum alloy sheet at room temperature.*

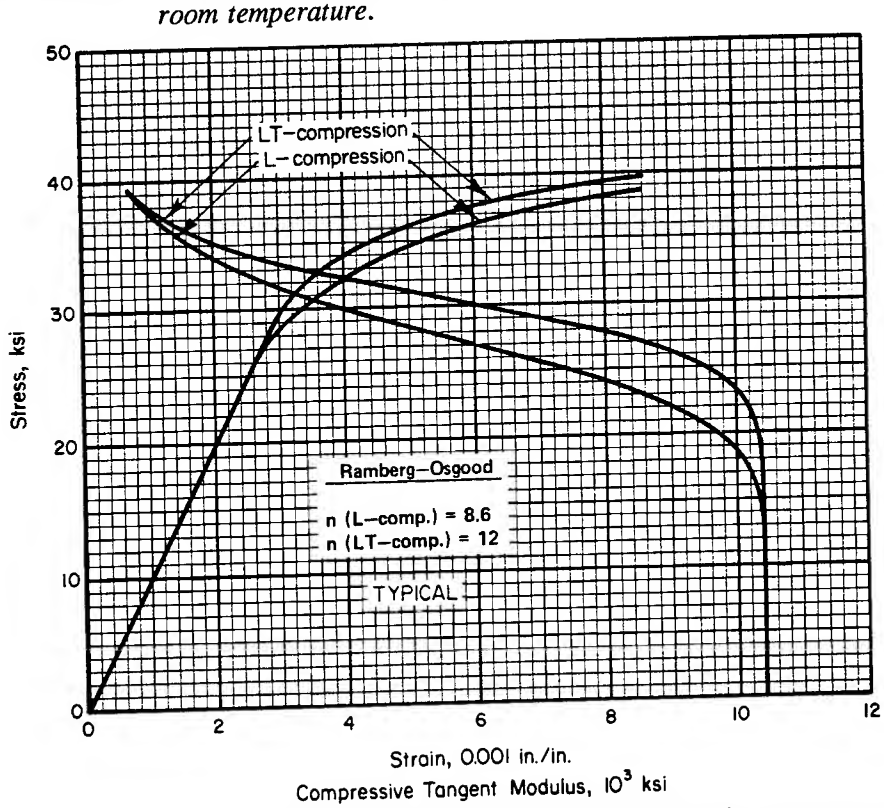

FIGURE 3.5.3.3.6(b). *Typical compressive stress-strain and compressive tangent-modulus curves for 5086-H34 aluminum alloy sheet at room temperature.*

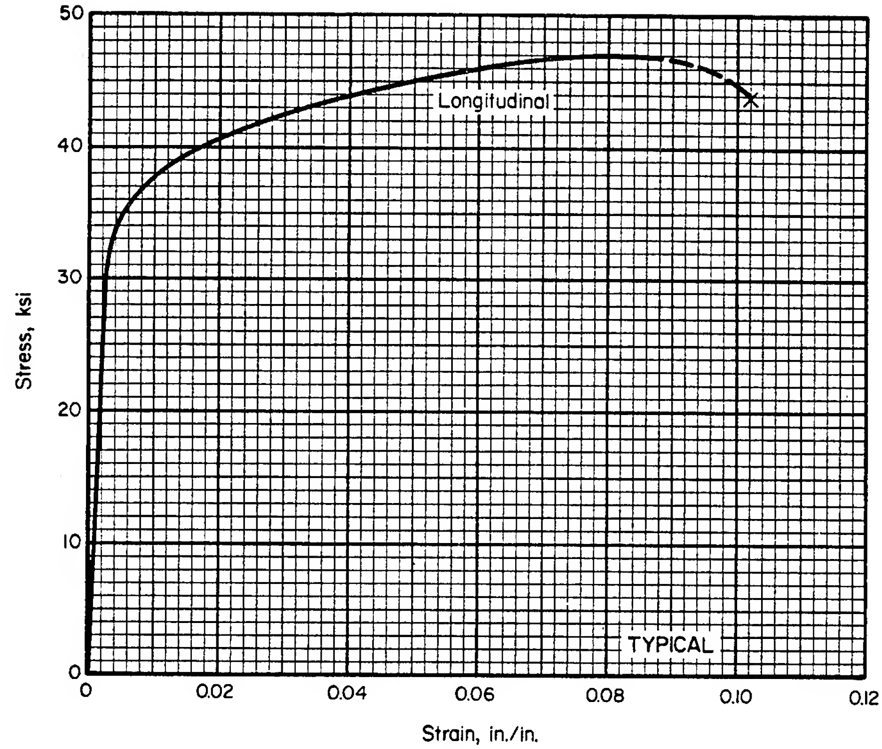

FIGURE 3.5.3.3.6(c). *Typical tensile stress-strain curve (full range) for 5086-H34 aluminum alloy sheet at room temperature.*

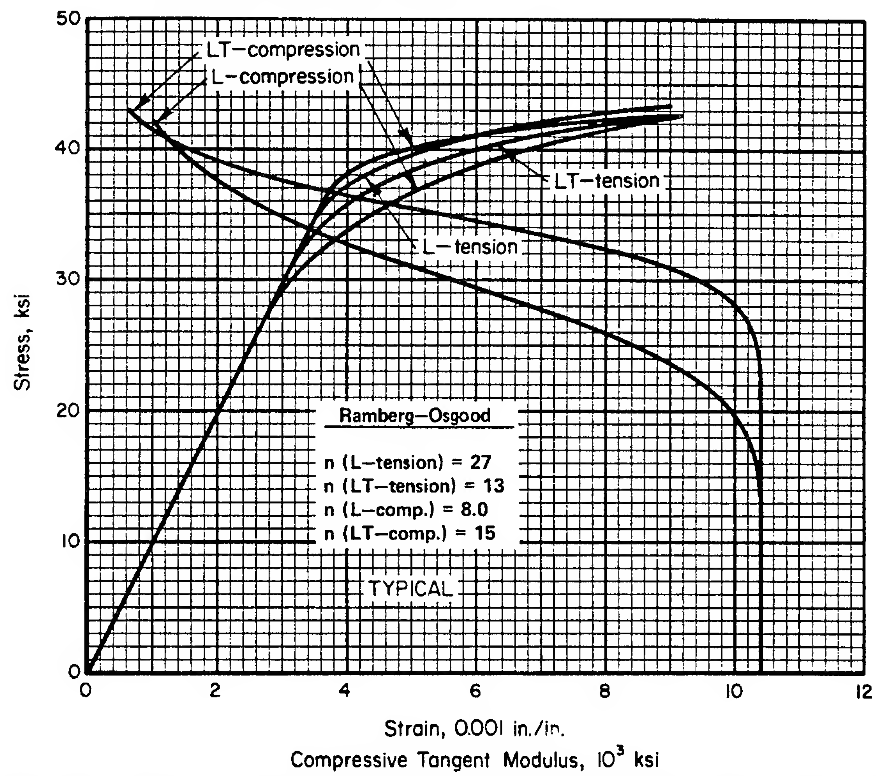

FIGURE 3.5.3.4.6. *Typical tensile and compressive stress-strain and compressive tangent-modulus curves for 5086-H36 aluminum alloy sheet at room temperature.*

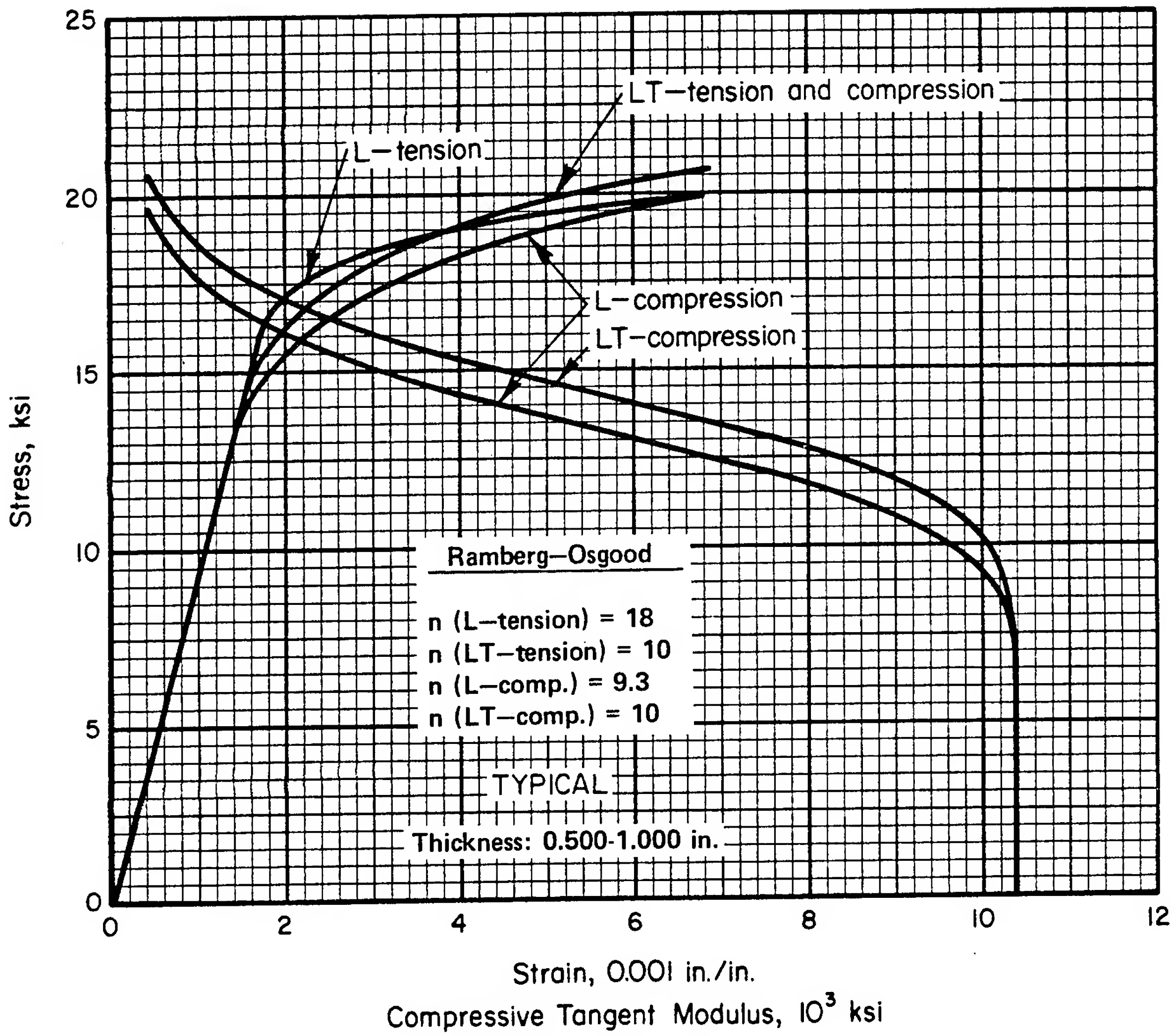

FIGURE 3.5.3.7.6. *Typical tensile and compressive stress-strain and compressive tangent-modulus curves for 5086-H112 aluminum alloy plate at room temperature.*

3.5.4 5454 ALLOY

3.5.4.0 *Comments and Properties.*—5454 is a tough medium-strength Al-Mg alloy. It is the highest strength alloy of the 5000 series which may be used at elevated temperatures without concern about resensitization to stress-corrosion cracking. Refer to Section 3.1.2.3 for comments regarding the resistance of the alloy to stress-corrosion cracking, and to Section 3.1.3.4 for comments regarding the weldability of the alloy.

Materials specifications for 5454 aluminum alloy are presented in Table 3.5.4.0(a). Room-temperature physical properties are shown in Table 3.5.4.0(b) and (c).

TABLE 3.5.4.0(a). *Material Specifications for 5454 Aluminum Alloy*

Specification	Form
QQ-A-250/10	Sheet and plate
QQ-A-200/6	Extruded bar, rod, and shapes

The temper index for 5454 is as follows:

Section	Temper
3.5.4.1	O
3.5.4.2	H32
3.5.4.3	H34

3.5.4.1 *O Temper.*—Figure 3.5.4.1.6 presents tensile and compressive stress-strain curves and this temper.

3.5.4.2 *H32 Temper.*—Figure 3.5.4.2.6 presents room-temperature tensile stress-strain curves for this temper.

3.5.4.3 *H34 Temper.*—Figures 3.5.4.3.6(a) and (b) present room-temperature tensile and compressive stress-strain and tangent-modulus curves for this temper.

TABLE 3.5.4.0(b). *Design Mechanical and Physical Properties of 5454 Aluminum Alloy Sheet, Plate, and Extrusion*

Specification	QQ-A-250/10							QQ-A-200/6		
Form	Sheet and plate							Extrusion		
Temper	O		H32		H34	H112		O	H111	H112
Thickness, in.	0.020-3.000		0.020-2.000		0.020-1.000	0.250-0.499	0.500-3.000	≤5.000[a]	≤5.000[a]	≤5.000[a]
Basis	A	B	A	B	S	S	S	S	S	S
Mechanical Properties:										
F_{tu}, ksi:										
L	31	32	36	37	39	32	31	31	33	31
LT	31	32	36	37	39	32	31	...	...	31
F_{ty}, ksi:										
L	12	13	26	27	29	18	12	12	19	12
LT	12	13	24	25	28	18	12	...	...	12
F_{cy}, ksi:										
L	12	13	24	25	27	17	12	12	...	12
LT	12	13	26	27	29	18	12	...	...	12
F_{su}, ksi	19	20	21	22	23	20	19	...	...	19
F_{bru}, ksi:										
(e/D = 1.5)	46	48	52	54	57	48	46	...	...	43
(e/D = 2.0)	62	64	72	74	78	64	62	...	...	56
F_{bry}, ksi:										
(e/D = 1.5)	20	22	36	38	41	25	20	...	...	20
(e/D = 2.0)	24	26	44	46	49	31	24	...	...	24
e, percent (S-basis):										
L	b	...	b	...	b	8	b	14	12	12
E, 10^3 ksi	10.2									
E_c, 10^3 ksi	10.4									
G, 10^3 ksi	3.85									
μ	0.33									
Physical Properties:										
ω, lb/in.^{3}	0.097									
C, Btu/(lb)(F)	0.23 (at 212 F)									
K, Btu/[(hr)(ft^3)(F)/ft]	78 (at 77 F)									
α, 10^{-6} in./in./F	13.1 (68 to 212 F)									

[a]Cross-sectional area ≤32.
[b]See Table 3.5.4.0(c).

TABLE 3.5.4.0(c). *Minimum Elongation Values for 5454 Aluminum Alloy Sheet and Plate*

Temper	Thickness range, inch	Elongation (L), percent
O	0.020-0.031	12
	0.030-0.050	14
	0.051-0.113	16
	0.114-3.000	18
H32	0.020-0.050	5
	0.051-0.249	8
	0.250-2.000	12
H34	0.020-0.050	4
	0.051-0.161	6
	0.162-0.249	7
	0.250-1.000	10
H112	0.500-2.000	11
	2.001-3.000	15

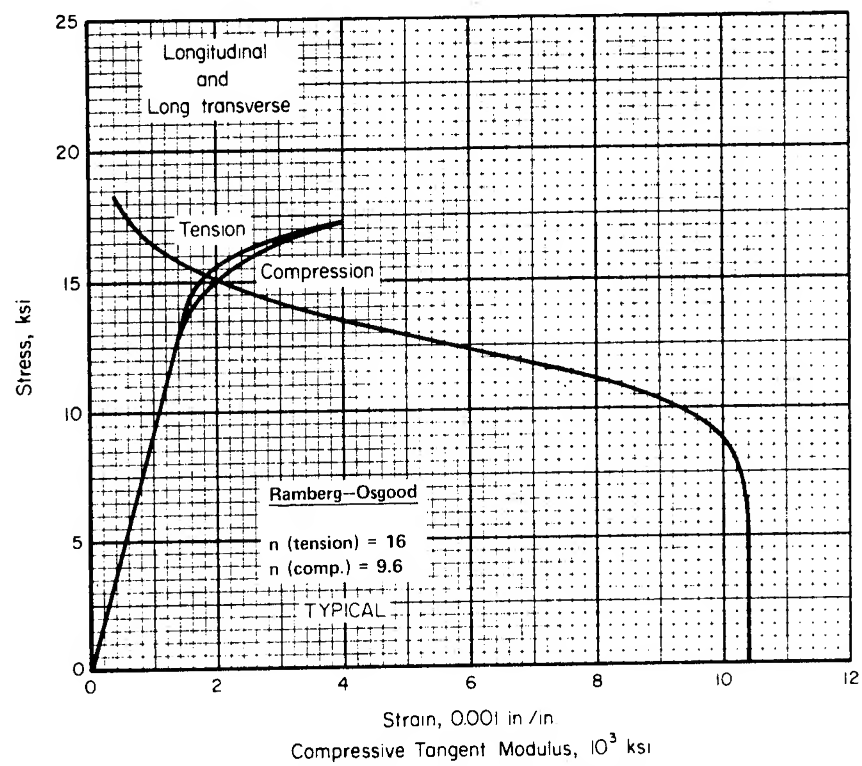

FIGURE 3.5.4.1.6. *Typical tensile and compressive stress-strain and compressive tangent-modulus curves for 5454-O aluminum alloy sheet, plate, extrusion at room temperature.*

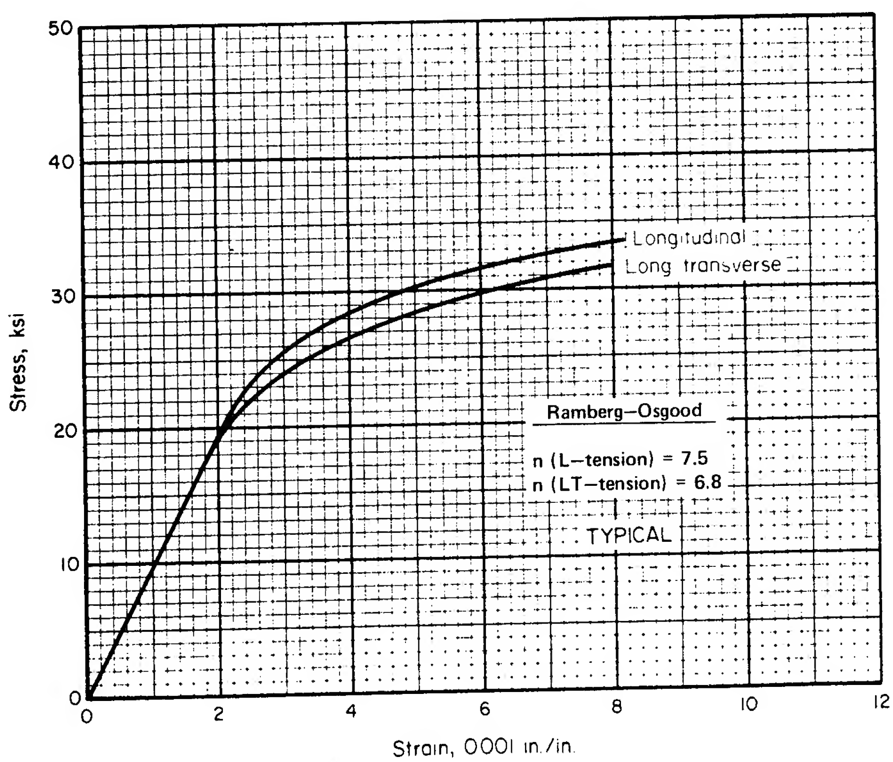

FIGURE 3.5.4.2.6. *Typical tensile stress-strain curves for 5454-H32 aluminum alloy plate at room temperature.*

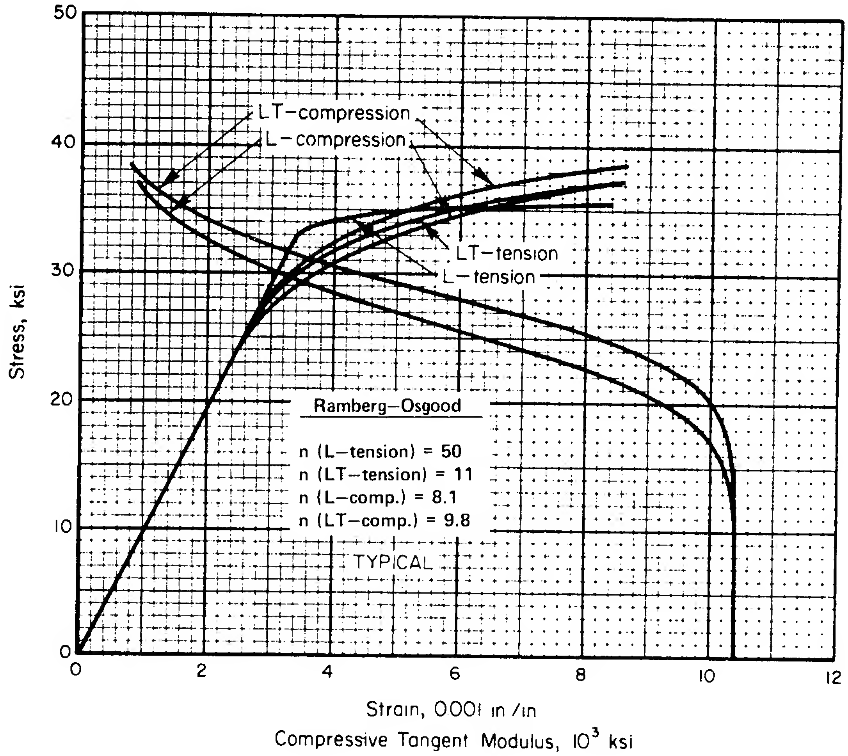

FIGURE 3.5.4.3.6(a). *Typical tensile and compressive stress-strain and compressive tangent-modulus curves for 5454-H34 aluminum alloy sheet at room temperature.*

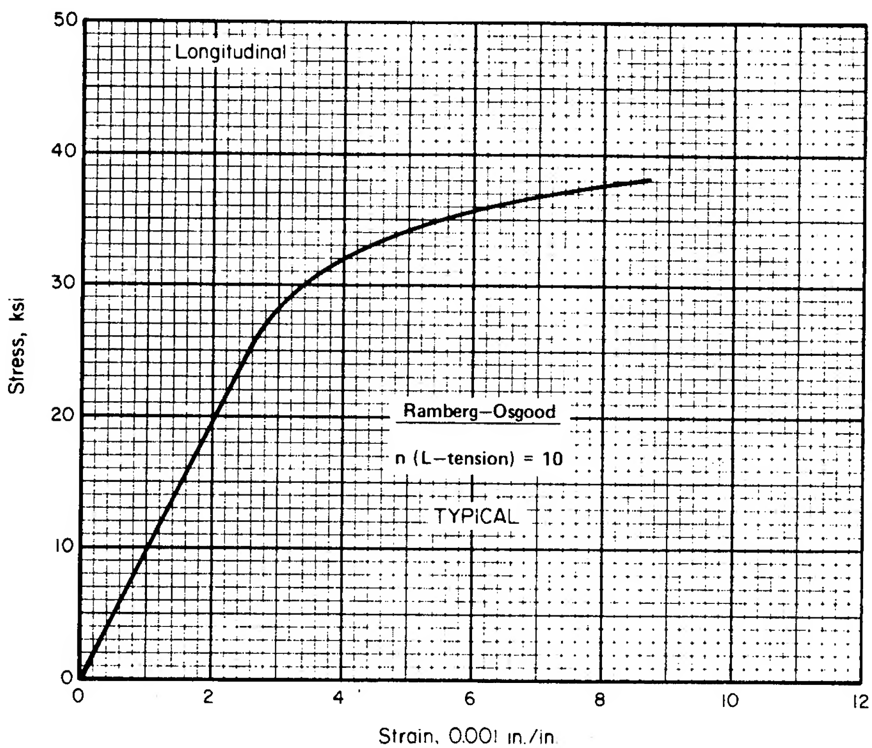

FIGURE 3.5.4.3.6(b). *Typical tensile stress-strain curve for 5454-H34 aluminum alloy plate at room temperature.*

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3.5.5 5456 ALLOY

3.5.5.0 *Comments and Properties.*—5456 is the highest strength alloy of the Al-Mg group. It has high resistance to corrosion, but should not be used in strain-hardened tempers at temperatures above 212 F because of possible sensitization to stress-corrosion cracking. Refer to Section 3.1.2.3 for comments regarding the resistance of the alloy to stress-corrosion cracking, and to Section 3.1.3.4 for comments regarding the weldability of the alloy.

Some material specifications for 5456 aluminum alloy are presented in Table 3.5.5.0(a). Room-temperature mechanical and physical properties are shown in Tables 3.5.5.0(b) and (c). The effect of temperature on physical properties is shown in Figure 3.5.5.0.

TABLE 3.5.5.0(a). *Material Specifications for 5456 Aluminum Alloy*

Specification	Form
QQ-A-250/9	Sheet and plate
QQ-A-200/7	Extruded bar, rod, and shapes

The temper index for 5456 is as follows:

Section	Temper
3.5.5.1	O
3.5.5.2	H111
3.5.5.3	H112
3.5.5.4	H321

3.5.5.1 *O Temper.*—Room-temperature tensile and compressive stress-strain and tangent-modulus curves for this temper are presented in Figures 3.5.5.1.6(a) and (b).

3.5.5.2 *H111 Temper.*—Room-temperature tensile and compressive stress-strain and tangent-modulus curves for this temper are presented in Figure 3.5.5.2.6.

3.5.5.3 *H112 Temper.*

3.5.5.4 *H321 Temper.*—Room-temperature tensile and compressive stress-strain and tangent-modulus curves for this temper are presented in Figure 3.5.5.4.6.

TABLE 3.5.5.0(b). *Design Mechanical and Physical Properties of 5456 Aluminum Alloy Sheet and Plate*

Specification	QQ-A-250/9										
Form	Sheet and plate										
Temper	O					H112		H321			
Thickness, in.	0.051-1.500	1.501-3.000	3.001-5.000	5.001-7.000	7.001-8.000	0.250-1.500	1.501-3.000	0.188-0.624	0.625-1.250	1.251-1.500	1.501-3.000
Basis	S	S	S	S	S	S	S	S	S	S	S
Mechanical Properties:											
F_{tu}, ksi:											
L	42	41	40	39	38	42	41	46	46	44	41
LT	42	...	...	...	...	...	...	46	45	43	...
F_{ty}, ksi:											
L	19	18	17	16	15	19	18	33	33	31	29
LT	19	...	...	...	...	...	...	30	29	28	...
F_{cy}, ksi:											
L	19	...	...	...	...	...	...	27	26	24	...
LT	19	...	...	...	...	...	...	33	31	29	...
F_{su}, ksi	26	...	...	...	...	...	...	27	27	25	...
F_{bru}, ksi:											
(e/D = 1.5)	63	...	...	...	...	...	...	67	67	64	...
(e/D = 2.0)	84	...	...	...	...	...	...	84	84	80	...
F_{bry}, ksi:											
(e/D = 1.5)	32	...	...	...	...	...	...	46	46	43	...
(e/D = 2.0)	38	...	...	...	...	...	...	53	53	50	...
e, percent:											
L	16	16	14	14	12	12	12	12	12	12	12
E, 10^3 ksi	10.2										
E_c, 10^3 ksi	10.4										
G, 10^3 ksi	3.85										
μ	0.33										
Physical Properties:											
ω, lb/in.^{3}	0.096										
C, Btu/(lb)(F)	0.23 (at 212 F)										
K, Btu/[(hr)(ft^2)(F)/ft]	...										
α, 10^{-6} in./in./F	See Figure 3.5.5.0										

TABLE 3.5.5.0(c). *Design Mechanical and Physical Properties of 5456 Aluminum Alloy Extrusion*

Specification	QQ-A-200/7		
Form	Extruded bar, rod, and shapes		
Temper	O	H111	H112
Cross-sectional area, in.^{2}	≤32		
Thickness or diameter, in.	≤5.000	≤5.000	≤5.000
Basis	S	S	S
Mechanical Properties:			
F_{tu}, ksi:			
L	41	42	41
LT	...	...	41
F_{ty}, ksi:			
L	19	26	19
LT	...	...	19
F_{cy}, ksi:			
L	19	...	19
LT	...	...	19
F_{su}, ksi	...	...	23
F_{bru}, ksi:			
(e/D = 1.5)	...	...	57
(e/D = 2.0)	...	...	74
F_{bry}, ksi:			
(e/D = 1.5)	...	...	34
(e/D = 2.0)	...	...	38
e, percent:			
L	14	12	12
E, 10^3 ksi	10.2		
E_c, 10^3 ksi	10.4		
G, 10^3 ksi	3.85		
μ	0.33		
Physical Properties:			
ω, lb/in.^{3}	0.096		
C, Btu/(lb)(F)	0.23 (at 212 F)		
K, Btu/[(hr)(ft^2)(F)/ft]	...		
α, 10^{-6} in./in./F	See Figure 3.5.5.0		

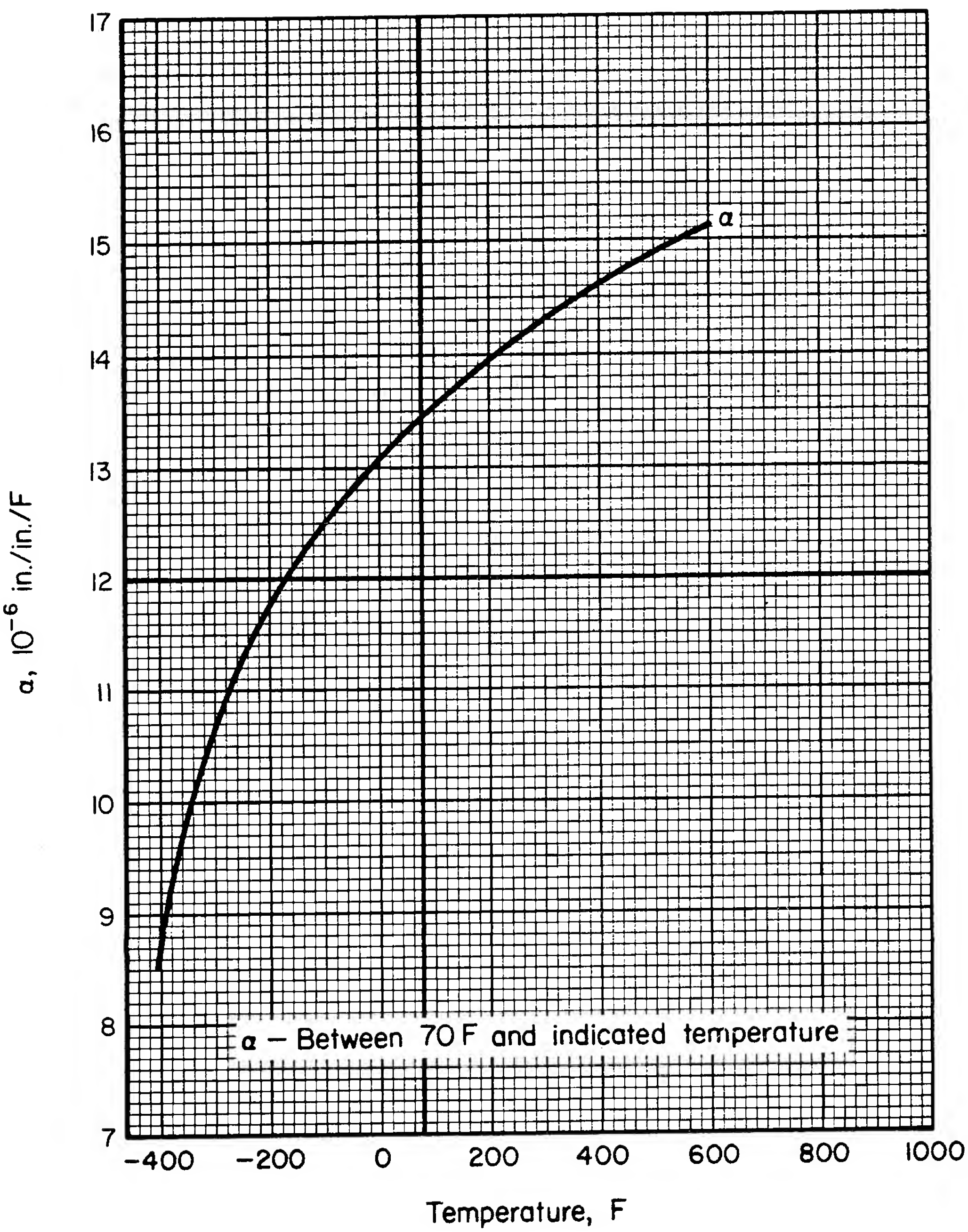

FIGURE 3.5.5.0. *Effect of temperature on the physical properties of 5456 aluminum alloy.*

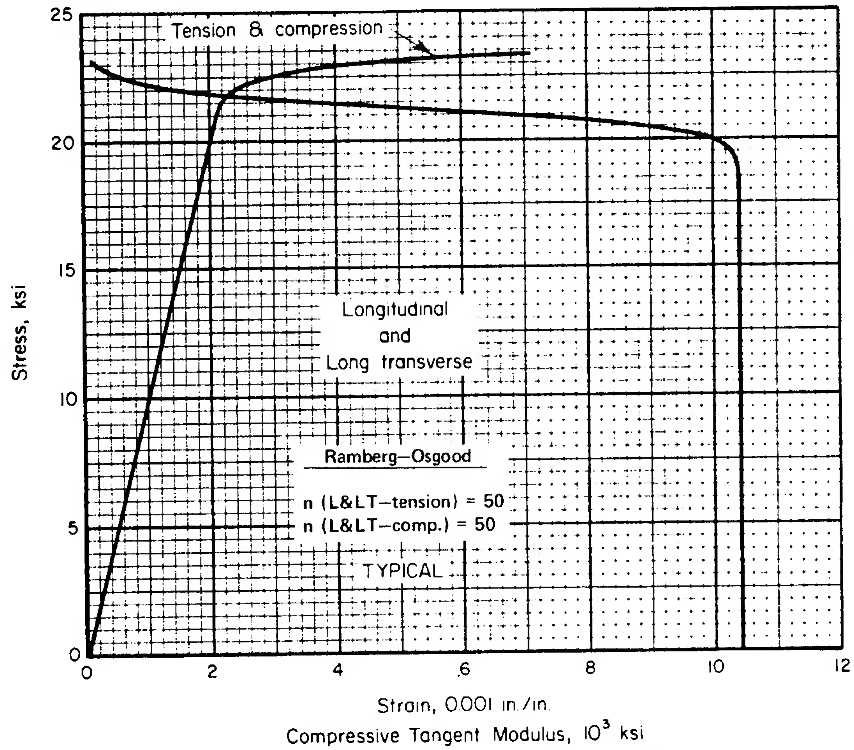

FIGURE 3.5.5.1.6(a). *Typical tensile and compressive stress-strain and compressive tangent-modulus curves for 5456-O aluminum alloy sheet and plate at room temperature.*

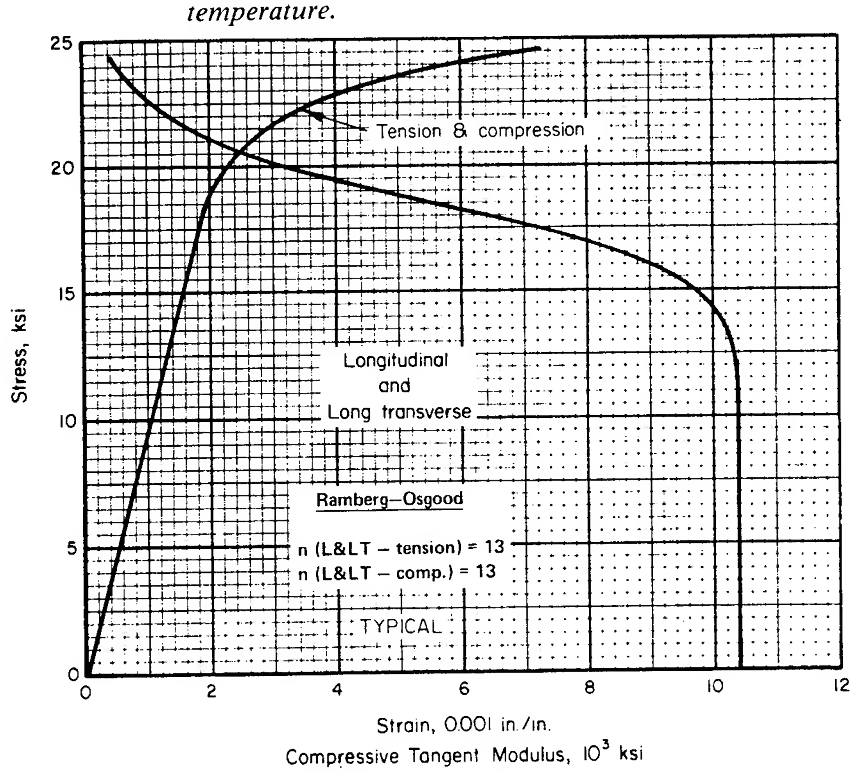

FIGURE 3.5.5.1.6(b). *Typical tensile and compressive stress-strain and compressive tangent-modulus curves for 5456-O aluminum alloy extrusion at room temperature.*

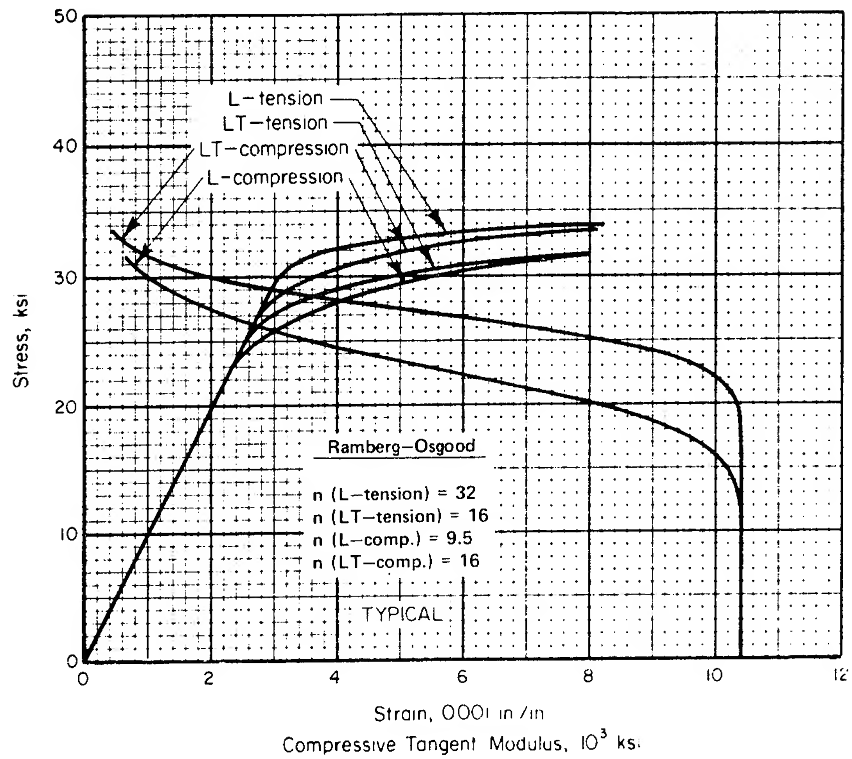

FIGURE 3.5.5.2.6. *Typical tensile and compressive stress-strain and compressive tangent-modulus curves for 5456-H111 aluminum alloy extrusion at room temperature.*

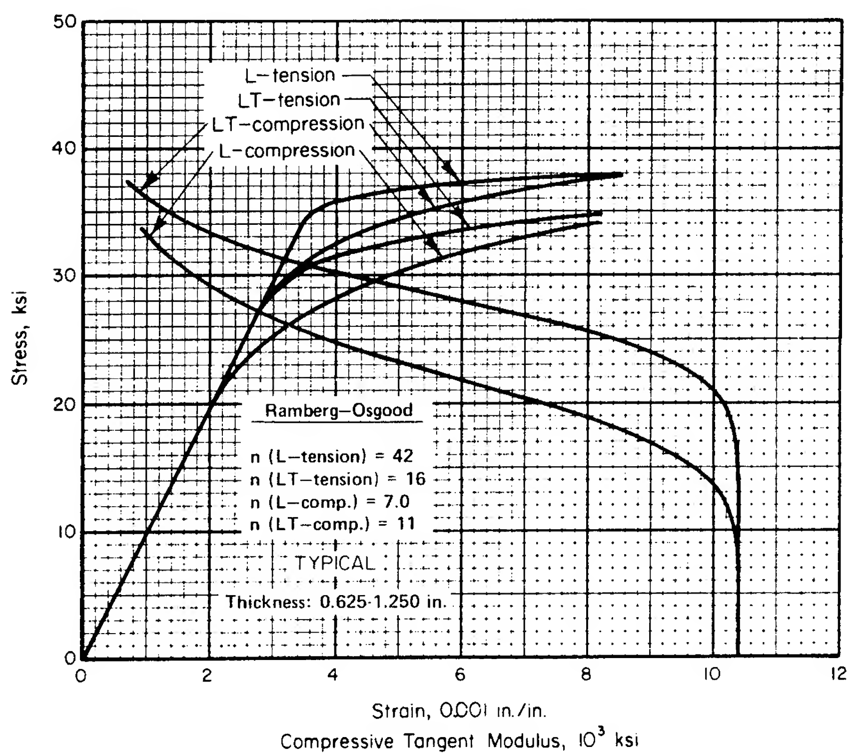

FIGURE 3.5.5.4.6. *Typical tensile and compressive stress-strain and compressive tangent-modulus curves for 5456-H321 aluminum alloy plate at room temperature.*

3.6 6000 Series Wrought Alloys

Alloys of the 6000 series contain magnesium and silicon as their principal alloying elements.

3.6.1 6013 ALLOY

3.6.1.0 *Comments and Properties*.--6013 is a Mg-Si-Cu-Mn alloy which is weldable. This alloy has 25 percent higher strength in the T6 temper than 6061-T6. It has improved toughness, fatigue strength, and stretch forming characteristics compared to 6061 with equivalent stress corrosion characteristics. Refer to 3.1.3.4 for comments regarding weldability of the alloy. Material specifications for 6013 are shown in Table 3.6.1.0(a). Room-temperature mechanical and physical properties are presented in Table 3.6.1.0(b).

TABLE 3.6.1.0(a). *Material Specifications for 6013 Aluminum Alloy*

Specification	Form
AMS 4347	Sheet (T4)
AMS 4216	Sheet (T6)

The temper index is as follows:

Section	Temper
3.6.1.1	T6

3.6.1.1 *T6 Temper*.--Stress-strain and tangent-modulus curves are presented in Figures 3.6.1.1.6(a) and (b).

TABLE 3.6.1.0(b). *Design Mechanical and Physical Properties of 6013 Aluminum Alloy Sheet*

Specification	AMS 4216 and AMS 4347		
Form	Sheet		
Temper	T6		
Thickness, in.	0.010-0.062	0.063-0.125	0.126-0.249
Basis	S	S	S
Mechanical Properties:			
F_{tu}, ksi:			
L	52	52	52
LT	52	52	52
F_{ty}, ksi:			
L	47	47	48
LT	46	46	46
F_{cy}, ksi:			
L	48	48	48
LT	48	48	49
F_{su}, ksi	32	32	32
F_{bru}[a], ksi:			
(e/D = 1.5)	85	85	85
(e/D = 2.0)	111	111	111
F_{bry}[a], ksi:			
(e/D = 1.5)	66	69	71
(e/D = 2.0)	76	80	82
e, percent:			
LT	8	8	8
E, 10^3 ksi	9.9		
E_c, 10^3 ksi	10.1		
G, 10^3 ksi	3.8		
μ	0.33		
Physical Properties:			
ω, lb/in.^{3}	0.098		
C, K, and α	...		

[a]Bearing values are "dry pin" values per Section 1.4.7.1.

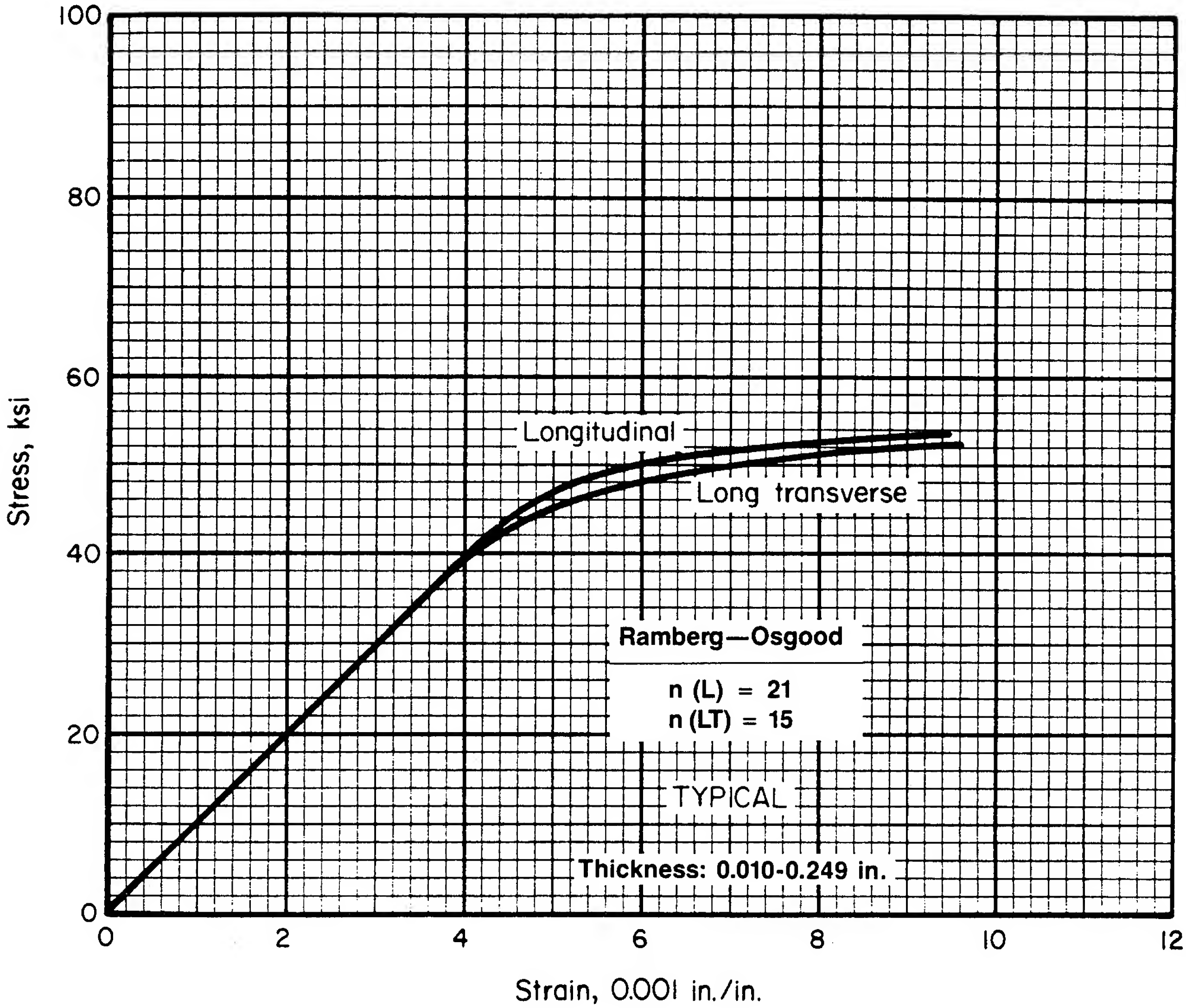

FIGURE 3.6.1.1.6(a). *Typical tensile stress-strain curves for 6013-T6 aluminum alloy sheet at room temperature.*

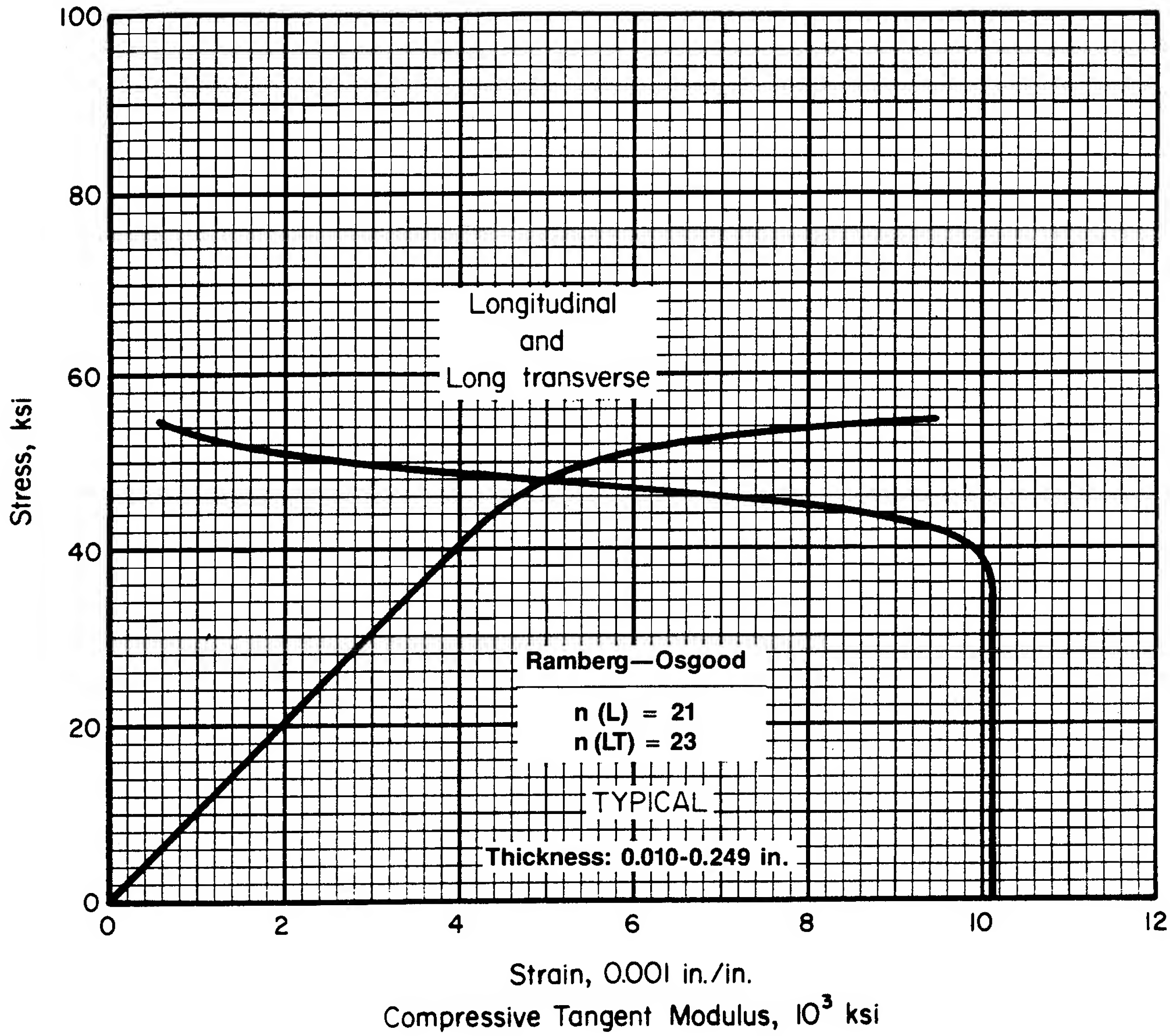

FIGURE 3.6.1.1.6(b). *Typical compressive stress-strain and compressive tangent-modulus curves for 6013-T6 aluminum alloy sheet at room temperature.*

3.6.2 6061 ALLOY

3.6.2.0 *Comments and Properties.*—6061 has been used in a wide range of applications, including cryogenic applications requiring high toughness. Refer to Section 3.1.3.4 for comments regarding the weldability of the alloy.

Material specifications for 6061 are presented in Table 3.6.2.0(a). Room-temperature mechanical and physical properties are shown in Tables 3.6.2.0(b) through (g). The effect of temperature on the physical properties is shown in Figure 3.6.2.0.

TABLE 3.6.2.0(a). *Material Specifications for 6061 Aluminum Alloy*

Specification	Form
AMS 4025	Sheet and plate
AMS 4026	Sheet and plate
AMS 4027	Sheet and plate
QQ-A-250/11	Sheet and plate
AMS 4115	Bar and rod, rolled or cold-finished
AMS 4116	Bar and rod, cold-finished
AMS 4117	Bar and rod, rolled or cold-finished
QQ-A-225/8	Rolled bar, rod, and shapes
AMS 4160	Extrusion
AMS 4161	Extrusion
AMS 4172	Extrusion
QQ-A-200/8	Extruded rod, bar, shapes, and tubing
MIL-A-22771	Forging
AMS 4080	Tubing, seamless, drawn
AMS 4082	Tubing, seamless, drawn
WW-T-700/6	Seamless drawn tubing
MIL-P-25995	Pipe
AMS 4127	Forging
AMS 4248	Hand forging
QQ-A-367	Forging

The temper index for 6061 is as follows:

Section	Temper
3.6.2.1	T4, T42, T451, T4510, and T4511
3.6.2.2	T6, T62, T651, T652, T6510, and T6511

3.6.2.1 *T4, T42, T451, T4510, and T4511 Tempers.*—For effect of temperature on modulus values, use Figure 3.6.2.2.4.

3.6.2.2 *T6, T651, T652, T6510, and T6511 Tempers.*—Figures 3.6.2.2.1(a) through (d), 3.6.2.2.4, and 3.6.2.2.5(a) and (b) present elevated temperature curves for various mechanical properties. Figures 3.6.2.2.6(a) through (k) contain tensile and compression stress-strain curves at room temperature and elevated temperatures, and tangent-modulus curves at room temperature for various products and tempers. Figures 3.6.2.2.6(l) through (o) present full-range tensile stress-strain curves at room temperature for various products and tempers. Figure 3.6.2.2.8 contains unnotched fatigue data for various wrought products at room temperature.

TABLE 3.6.2.0(b$_1$). *Design Mechanical and Physical Properties of 6061 Aluminum Alloy Sheet*

Specification	AMS 4026 and QQ-A-250/11		QQ-A-250/11	AMS 4025, AMS 4027 and QQ-A-250/11	
Form	Sheet				
Temper	T4		T42[a]	T6 and T62[b]	
Thickness, in.	0.010-0.249		0.010-0.249	0.010-0.249	
Basis	A	B	S	A	B
Mechanical Properties:					
F_{tu}, ksi:					
L	...	...	...	42	43
LT	30	32	30	42	43
F_{ty}, ksi:					
L	...	...	...	36	38
LT	16	18	14	35	37
F_{cy}, ksi:					
L	...	...	...	35	37
LT	16	18	...	36	38
F_{su}, ksi	20	21	...	27	28
F_{bru}, ksi:					
(e/D = 1.5)	48	51	...	67	69
(e/D = 2.0)	63	67	...	88	90
F_{bry}, ksi:					
(e/D = 1.5)	22	25	...	50	53
(e/D = 2.0)	26	29	...	58	61
e, percent (S-basis):					
LT	c	...	c	c	...
E, 10^3 ksi	9.9				
E_c, 10^3 ksi	10.1				
G, 10^3 ksi	3.8				
μ	0.33				
Physical Properties:					
ω, lb/in.^{3}	0.098				
C, K, and α	See Figure 3.6.2.0				

[a]Design allowables were based upon data obtained from testing samples of material, supplied in the O or F temper, which were heat treated to demonstrate response to heat treatment by suppliers. Properties obtained by the user may be lower than those listed if the material has been formed or otherwise cold or hot worked, particularly in the annealed temper, prior to solution heat treatment.

[b]Design allowables were based upon data obtained from testing T6 sheet and from testing samples of sheet, supplied in the O or F temper, which were heat treated to T62 temper to demonstrate response to heat treatment by suppliers. Properties obtained may be lower than those listed if the material has been formed or otherwise cold worked, particularly in the annealed temper, prior to solution heat treatment.

[c]See Table 3.6.2.0(b$_3$).

TABLE 3.6.2.0(b$_2$). *Design Mechanical and Physical Properties of 6061 Aluminum Alloy Plate*

Specification	AMS 4026 and QQ-A-250/11				QQ-A-250/11		AMS 4025, AMS 4027 and QQ-A-250/11					
Form	Plate											
Temper	T451				T42[a]		T651 and T62[b]					
Thickness, in.	0.250-2.000		2.001-3.000		0.250-1.000	1.001-3.000	0.250-2.000		2.001-3.000		3.001-4.000	4.001-6.000[d]
Basis	A	B	A	B	S	S	A	B	A	B	S	S
Mechanical Properties:												
F_{tu}, ksi:												
L	...	...	...	...	...	...	42	43	...	...	...	...
LT	30	32	30	32	30	30	42	43	42	43	42	40
F_{ty}, ksi:												
L	...	...	...	...	...	...	36	38	...	...	...	...
LT	16	18	16	18	14	14	35	37	35	37	35	35
F_{cy}, ksi:												
L	...	...	...	...	...	...	35	37	...	...	...	...
LT	16	18	...	...	...	...	36	38	...	...	...	...
F_{su}, ksi	20	21	...	...	...	...	27	28	...	...	...	...
F_{bru}, ksi:												
(e/D = 1.5)	48	51	...	...	...	...	67	69	...	...	...	...
(e/D = 2.0)	63	67	...	...	...	...	88	90	...	...	...	...
F_{bry}, ksi:												
(e/D = 1.5)	22	25	...	...	...	...	50	53	...	...	...	...
(e/D = 2.0)	26	29	...	...	...	...	58	61	...	...	...	...
e, percent (S-basis):												
LT	c	...	16	...	18	16	c	...	6	...	6	6
E, 10^3 ksi	9.9											
E_c, 10^3 ksi	10.1											
G, 10^3 ksi	3.8											
μ	0.33											
Physical Properties:												
ω, lb/in.^{3}	0.098											
C, K, and α	See Figure 3.6.2.0											

[a]Design allowables were based upon data obtained from testing samples of material, supplied in the O temper, which were heat treated to demonstrate response to heat treatment by suppliers. Properties obtained by the user may be lower than those listed if the material has been formed or otherwise cold or hot worked, particularly in the annealed temper, prior to solution heat treatment.

[b]Design allowables were based upon data obtained from testing T651 plate and from testing samples of plate, supplied in the O temper, which were heat treated to demonstrate response to heat treatment by suppliers. Properties obtained may be lower than those listed if the material has been formed or otherwise cold worked, particularly in the annealed temper, prior to solution heat treatment.

[c]See Table 3.6.2.0(b$_3$).

[d]Properties for this thickness apply only to T651 temper.

TABLE 3.6.2.0(b_3). *Minimum Elongation Values for 6061 Aluminum Alloy Sheet and Plate*

Temper and Product	Thickness, inch	Elongation (LT), percent
T4 or T42 sheet	0.010-0.020	14
	0.021-0.249	16
T451 plate	0.250-1.000	18
	1.001-2.000	16
T6 or T62 sheet	0.010-0.020	8
	0.021-0.249	10
T651 or T62 plate	0.250-0.499	10
	0.500-1.000	9
	1.001-2.000	8

TABLE 3.6.2.0(c_1). *Design Mechanical and Physical Properties of 6061 Aluminum Alloy Tube and Pipe*

Specification	WW-T-700/6		AMS 4080, AMS 4082, and WW-T-700/6	MIL-P-25995	
Form	Drawn tube			Pipe	
Temper	T4	T42[a]	T6[b] and T62	T6	
Wall thickness, in.	0.025-0.500	0.025-0.500	0.025-0.500	0.049-0.154	0.065-0.687
Outside Diameter, in.	...			<1.000	1.000-12.000
Basis	S	S	S	S	S
Mechanical Properties:					
F_{tu}, ksi:					
L	30	30	42	42	38
F_{ty}, ksi:					
L	16	14	35	35	35
F_{cy}, ksi:					
L	14	...	34	34	34
F_{su}, ksi	20	...	27	27	24
F_{bru}, ksi:					
(e/D = 1.5)	48	...	67	67	61
(e/D = 2.0)	63	...	88	88	80
F_{bry}, ksi:					
(e/D = 1.5)	22	...	49	49	49
(e/D = 2.0)	26	...	56	56	56
e, percent:					
L	c	c	c	12	10[d]
E, 10^3 ksi	9.9				
E_c, 10^3 ksi	10.1				
G, 10^3 ksi	3.8				
μ	0.33				
Physical Properties:					
ω, lb/in.^{3}	0.098				
C, K, and α	See Figure 3.6.2.0				

[a]Design allowables were based upon data obtained from testing samples of material, supplied in the O temper, which were heat treated to demonstrate response to heat treatment by suppliers. Properties obtained by the user may be lower than those listed if the material has been formed or otherwise cold or hot worked, particularly in the annealed temper, prior to solution heat treatment.

[b]Design allowables were based upon data obtained from testing T6 temper tube and from testing samples of tube, supplied in the O temper, which were heat treated to demonstrate response to heat treatment by suppliers. Properties obtained by the user may be lower than those listed if the material has been formed or otherwise cold worked, particularly in the annealed temper, prior to solution heat treatment.

[c]See Table 3.6.2.0(c_2).

[d]For wall thickness ≤0.249 inch, e = 8%.

TABLE 3.6.2.0(c_2). *Minimum Elongation Values for 6061 Aluminum Alloy Tubing*

Temper	Wall thickness, inch	Elongation (LT), percent	
		Full-section specimen	Cut-out specimen
T4 or T42	0.025-0.049	16	14
	0.050-0.259	18	16
	0.260-0.500	20	18
T6 or T62	0.025-0.049	10	8
	0.050-0.259	12	10
	0.260-0.500	14	12

TABLE 3.6.2.0(d). *Design Mechanical and Physical Properties of 6061 Aluminum Alloy Rolled, Drawn, or Cold-Finished Bar, Rod, and Shapes*

Specification	AMS 4116 & QQ-A-225/8	AMS 4128 & QQ-A-225/8	QQ-A-225/8	AMS 4117 & QQ-A-225/8	AMS 4128 & QQ-A-225/8	AMS 4115, AMS 4116, & QQ-A-225/8
Form	Rolled, drawn, or cold-finished rod and special shapes					
Condition	T4	T451	T42[a]	T6	T651	T62[a]
Cross-sectional area, in.^{2}	≤50					
Thickness, in.	≤8.000	0.500-8.000	≤8.000	≤8.000	0.500-8.000	≤8.000
Basis	S	S	S	S	S	S
Mechanical Properties:						
F_{tu}, ksi:						
L	30	30	30	42	42	42
F_{ty}, ksi:						
L	16	16	14	35	35	35
F_{cy}, ksi:						
L	14	14	...	34	34	...
F_{su}, ksi	20	20	...	27	27	...
F_{bru}, ksi:						
(e/D = 1.5)	48	48	...	67	67	...
(e/D = 2.0)	63	63	...	88	88	...
F_{bry}, ksi:						
(e/D = 1.5)	22	22	...	49	49	...
(e/D = 2.0)	26	26	...	56	56	...
e, percent:						
L	18	18	18	10	10	10
E, 10^3 ksi	9.9					
E_c, 10^3 ksi	10.1					
G, 10^3 ksi	3.8					
μ	0.33					
Physical Properties:						
ω, lb/in.^{3}	0.098					
C, K, and α	See Figure 3.6.2.0					

[a]Design allowables were based upon data obtained from testing samples of material, supplied in the O or F temper, which were heat treated to demonstrate response to heat treatment by suppliers.

TABLE 3.6.2.0(e). *Design Mechanical and Physical Properties of 6061 Aluminum Alloy Die Forging*

Specification	AMS 4127, MIL-A-22771, and QQ-A-367
Form	Die forging
Temper	T6 and T652
Thickness, in.	≤ 4.000[a]
Basis	S
Mechanical Properties:	
F_{tu}, ksi:	
L	38
T[b]	38
F_{ty}, ksi:	
L	35
T[b]	35
F_{cy}, ksi:	
L	36
T[b]	36
F_{su}, ksi	25
F_{bru}, ksi:	
(e/D = 1.5)	61
(e/D = 2.0)	76
F_{bry}, ksi:	
(e/D = 1.5)	54
(e/D = 2.0)	61
e, percent:	
L	7
T[b]	5
E, 10^3 ksi	9.9
E_c, 10^3 ksi	10.1
G, 10^3 ksi	3.8
μ	0.33
Physical Properties:	
ω, lb/in.^{3}	0.098
C, K, and α	See Figure 3.6.2.0

[a]Thickness at the time of heat treatment. When die forgings are machined before heat treatment, the mechanical properties are applicable provided the as-forged thickness is not greater than twice the thickness at the time of heat treatment.
[b]For die forgings, T indicates any grain direction not within ± 15° of being parallel to the forging flow lines. Specimens to test transverse properties should be located as close to the short transverse direction as possible.

TABLE 3.6.2.0(f). *Design Mechanical and Physical Properties of 6061 Aluminum Alloy Hand Forging*

Specification	AMS 4127, AMS 4248, MIL-A-22771, and QQ-A-367		
Form	Hand forging		
Temper	T6[a] and T652		
Cross-sectional area, in.^{2}	≤256		
Thickness, in.	≤2.000	2.001-4.000	4.001-8.000
Basis	S	S	S
Mechanical Properties:			
F_{tu}, ksi:			
L	38	38	37
LT	38	38	37
ST	...	37	35
F_{ty}, ksi:			
L	35	35	34
LT	35	35	34
ST	...	33	32
F_{cy}, ksi:			
L	36	36	35
LT	36	36	35
ST	...	34	33
F_{su}, ksi	25	25	24
F_{bru}, ksi:			
(e/D = 1.5)	61	61	59
(e/D = 2.0)	76	76	74
F_{bry}, ksi:			
(e/D = 1.5)	54	54	53
(e/D = 2.0)	61	61	59
e, percent:			
L	10	10	8
LT	8	8	6
ST	...	5	4
E, 10^3 ksi	9.9		
E_c, 10^3 ksi	10.1		
G, 10^3 ksi	3.8		
μ	0.33		
Physical Properties:			
ω, lb/in.^{3}	0.098		
C, K, and α	See Figure 3.6.2.0		

[a]When hand forgings are machined before heat treatment, the section thickness at time of heat treatment shall determine the minimum mechanical properties as long as the original (as-forged) thickness does not exceed the maximum thickness for the alloy as shown in the table.

TABLE 3.6.2.0(g). *Design Mechanical and Physical Properties of 6061 Aluminum Alloy Extruded Rod, Bar, and Shapes*

Specification	AMS 4161, AMS 4172, & QQ-A-200/8	QQ-A-200/8	AMS 4160 & QQ-A-200/8	QQ-A-200/8			
Form	Extruded rod, bar, and shapes						
Temper	T4, T4510, and T4511	T42[a]	T62[a]	T6, T6510, and T6511			
Cross-sectional area, in.^{2}	...	...	...	≤32			
Thickness, in.	≤3.000	All	All	≤1.000		1.001-6.500	
Basis	S	S	S	A	B	A	B
Mechanical Properties:							
F_{tu}, ksi:							
L	26	26	38	38	41	38	41
LT	...	...	...	37	40	33	35
F_{ty}, ksi:							
L	16	12	35	35	38	35	38
LT	...	...	...	33	36	28	31
F_{cy}, ksi:							
L	14	...	...	34	37	34	37
LT	...	...	...	35	38	30	33
F_{su}, ksi	16	...	...	26	28	19	21
F_{bru}[b], ksi:							
(e/D = 1.5)	42	...	...	64	69	52	57
(e/D = 2.0)	55	...	...	82	88	69	74
F_{bry}[b], ksi:							
(e/D = 1.5)	22	...	...	54	58	42	46
(e/D = 2.0)	26	...	...	60	65	50	55
e, percent (S-basis):							
L	16	16	10[c]	10[c]	...	10	...
E, 10^3 ksi	9.9						
E_c, 10^3 ksi	10.1						
G, 10^3 ksi	3.8						
μ	0.33						
Physical Properties:							
ω, lb/in.^{3}	0.098						
C, K, and α	See Figure 3.6.2.0						

[a]Design allowables were based upon data obtained from testing samples of material, supplied in the O to F temper which were heat treated to demonstrate response to heat treatment by suppliers. Properties obtained by the user, however, may be lower than those listed if the material has been formed or otherwise cold or hot worked, particularly in the annealed temper, prior to solution heat treatment.
[b]Bearing values are "dry pin" values per Section 1.4.7.1.
[c]For thicknesses ≤0.249 inch, e = 8%.

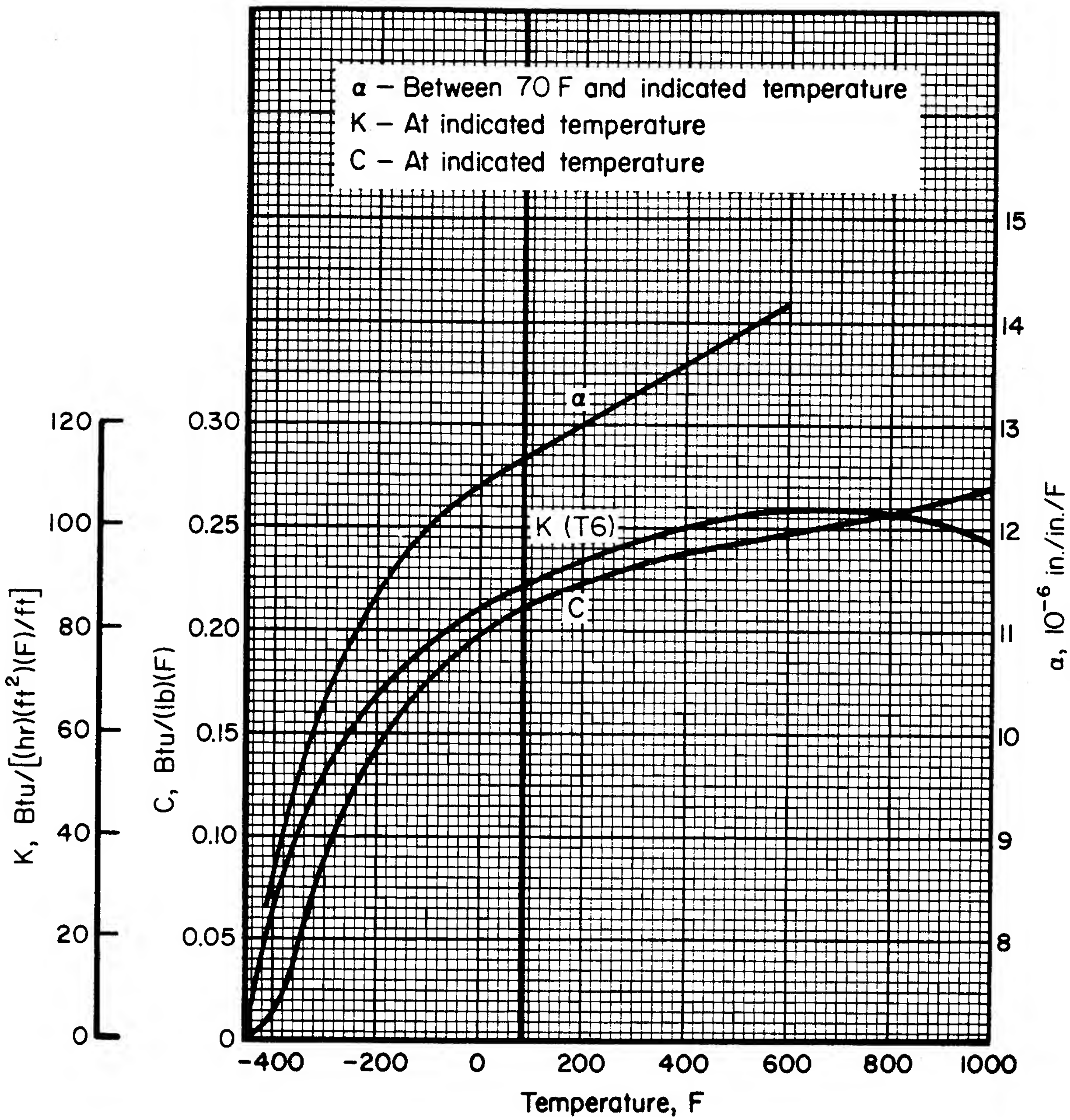

FIGURE 3.6.2.0. *Effect of temperature on the physical properties of 6061 aluminum alloy.*

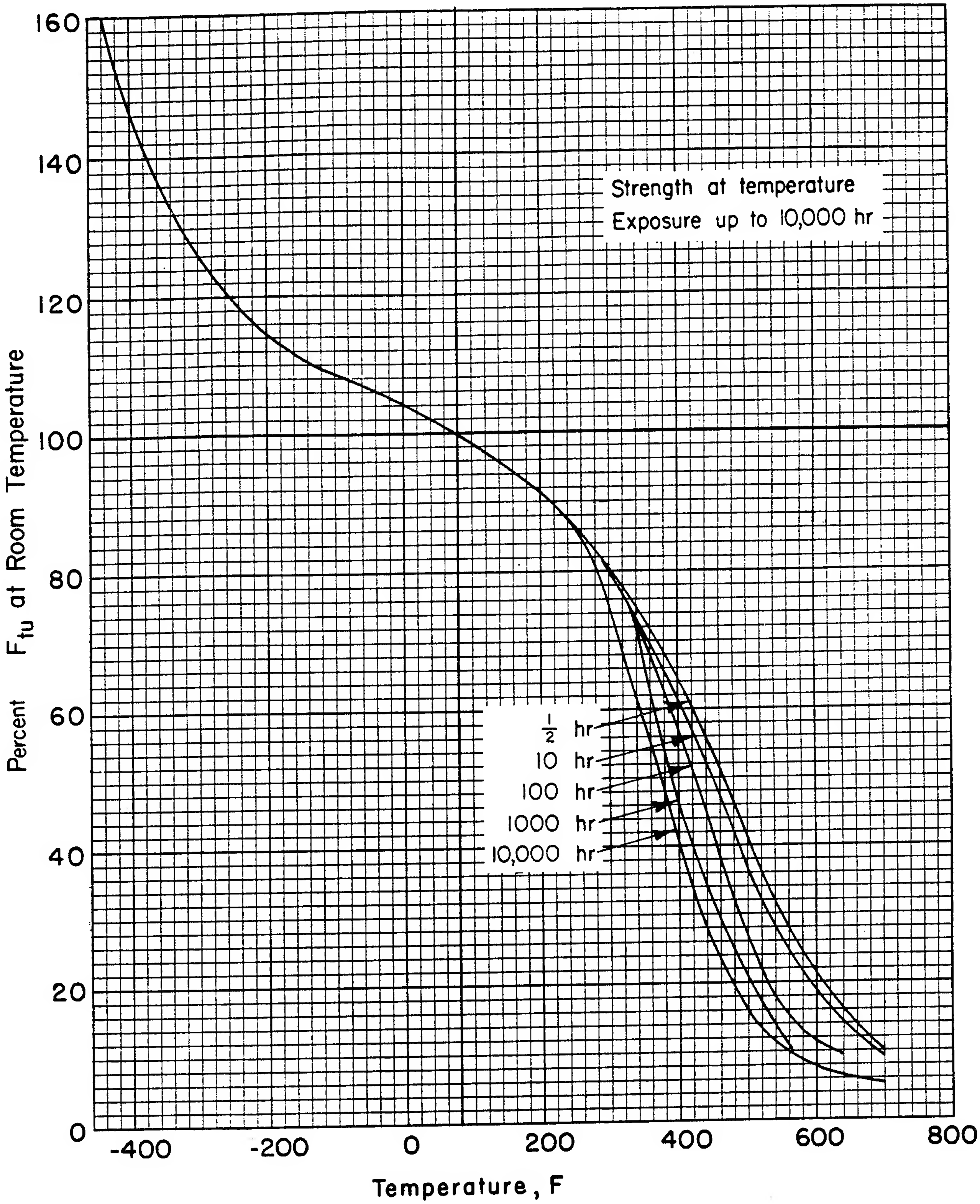

FIGURE 3.6.2.2.1(a). *Effect of temperature on the ultimate tensile strength (F_{tu}) of 6061-T6 aluminum alloy (all products).*

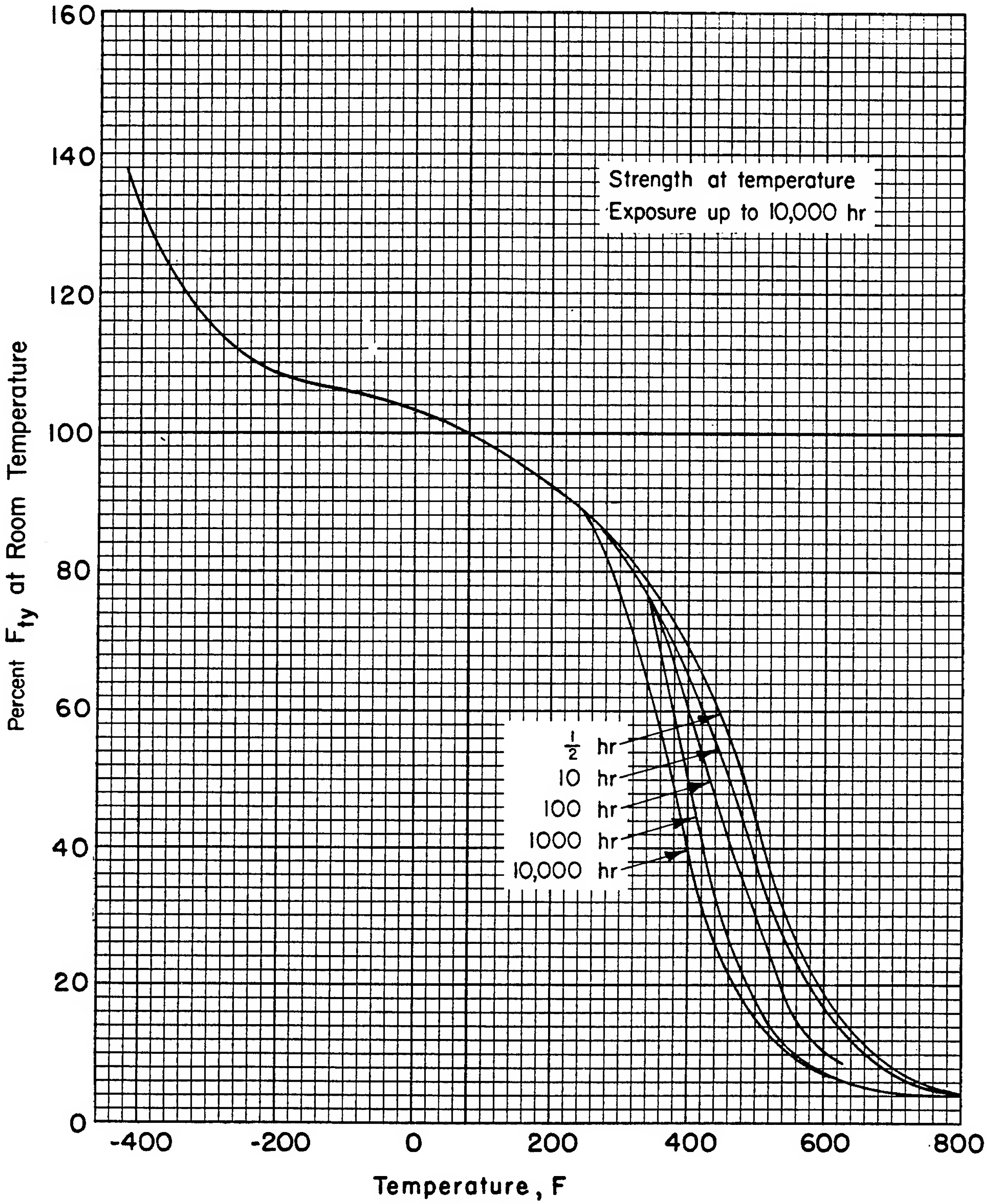

FIGURE 3.6.2.2.1(b). *Effect of temperature on the tensile yield strength (F_{ty}) of 6061-T6 aluminum alloy (all products).*

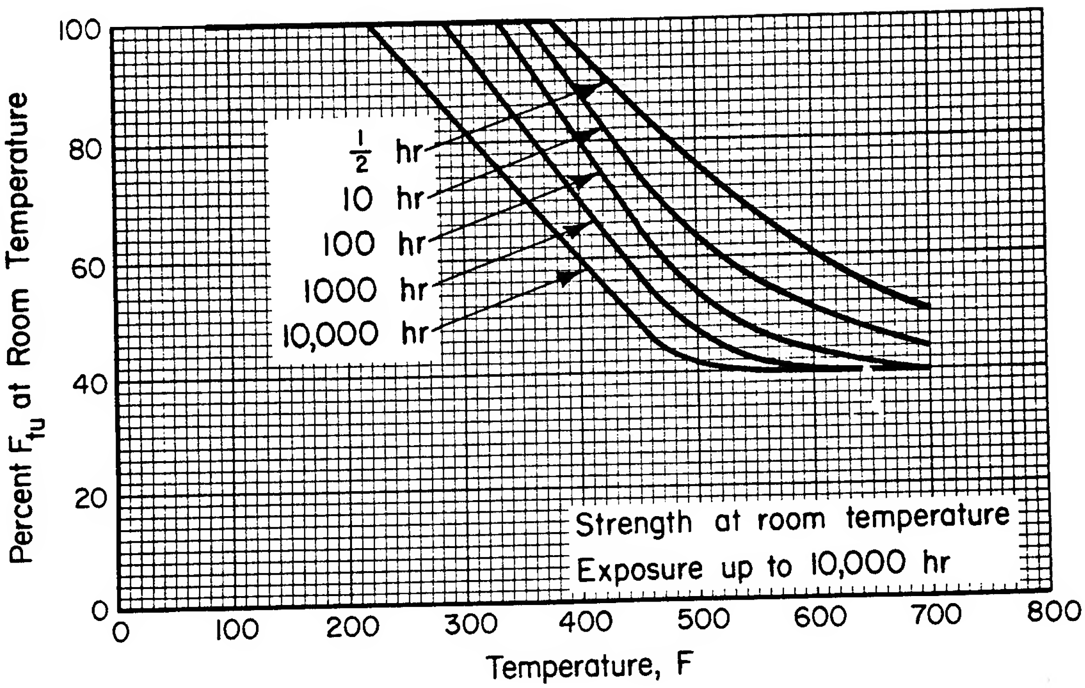

FIGURE 3.6.2.2.1(c). *Effect of exposure at elevated temperatures on the room-temperature ultimate tensile strength (F_{tu}) of 6061-T6 aluminum alloy (all products).*

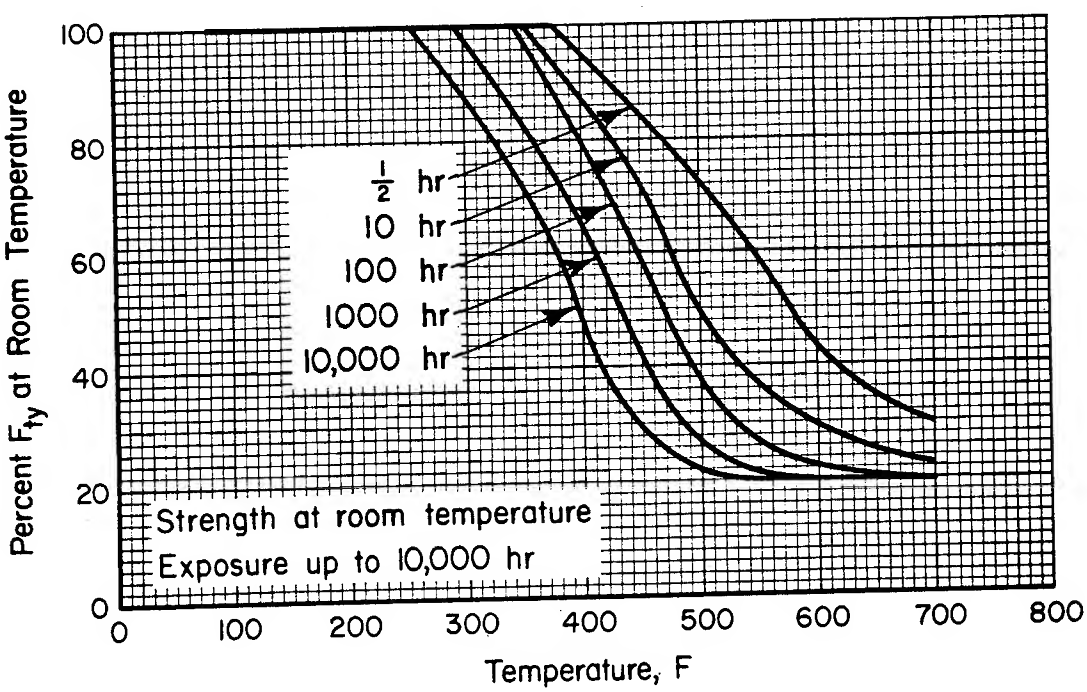

FIGURE 3.6.2.2.1(d). *Effect of exposure at elevated temperatures on the room-temperature tensile yield strength (F_{ty}) of 6061-T6 aluminum alloy (all products).*

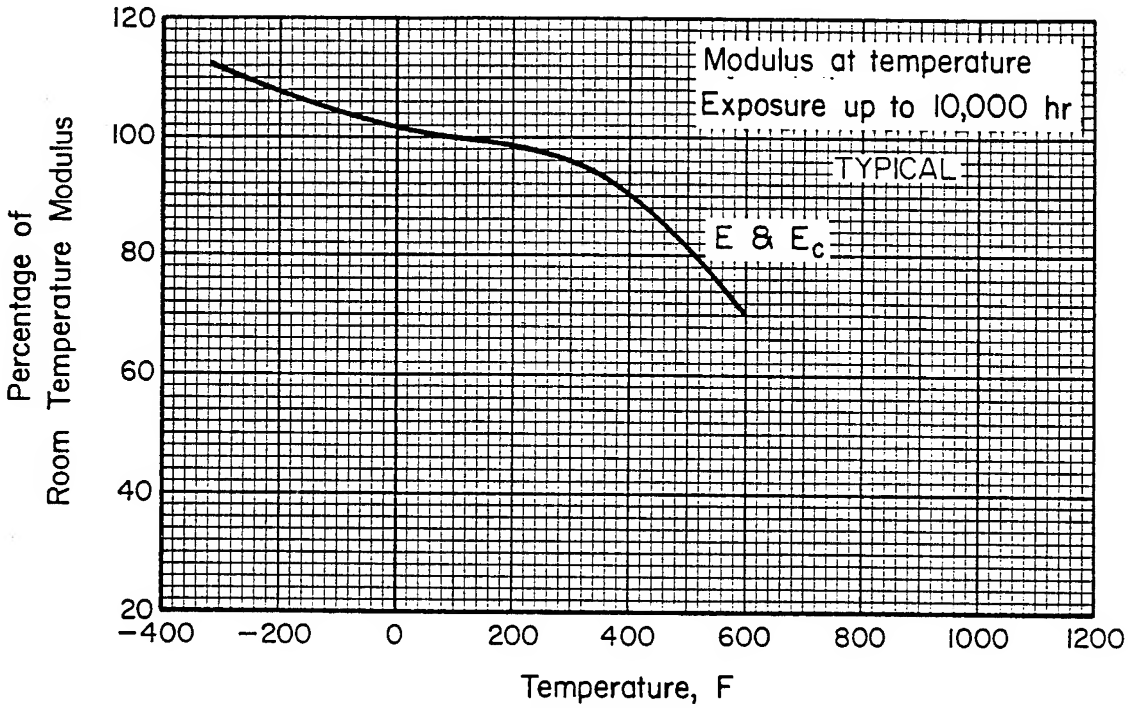

FIGURE 3.6.2.2.4. *Effect of temperature on the tensile and compressive moduli (E and E_c) of 6061 aluminum alloy.*

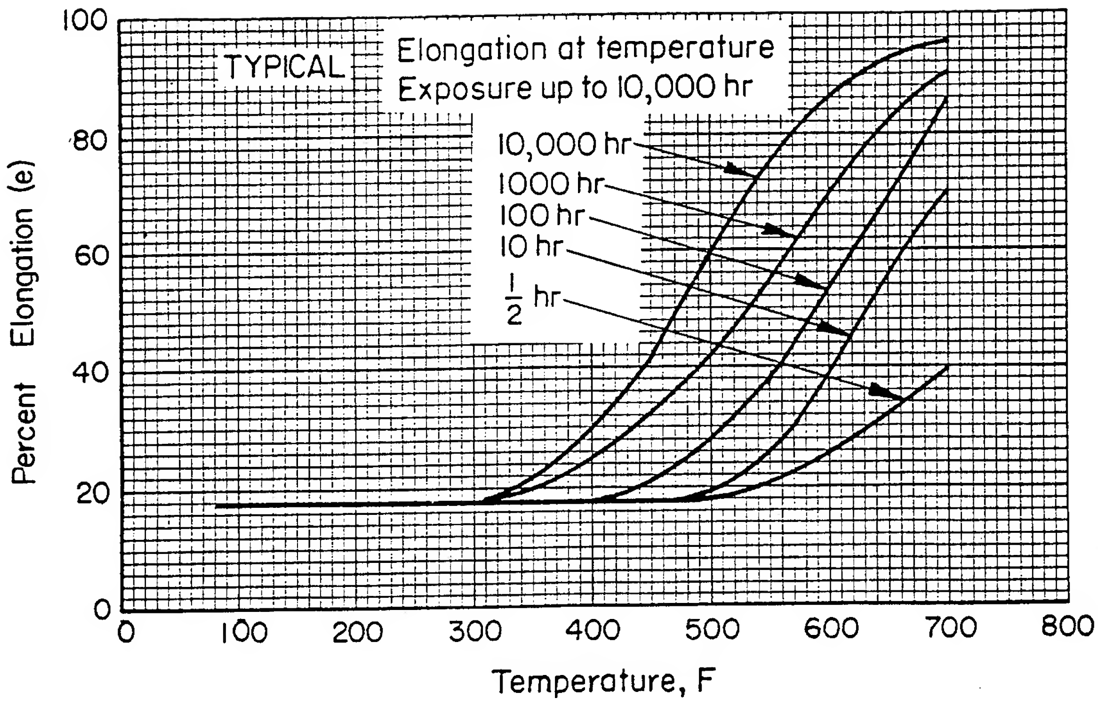

FIGURE 3.6.2.2.5(a). *Effect of temperature on the elongation of 6061-T6 aluminum alloy (all products).*

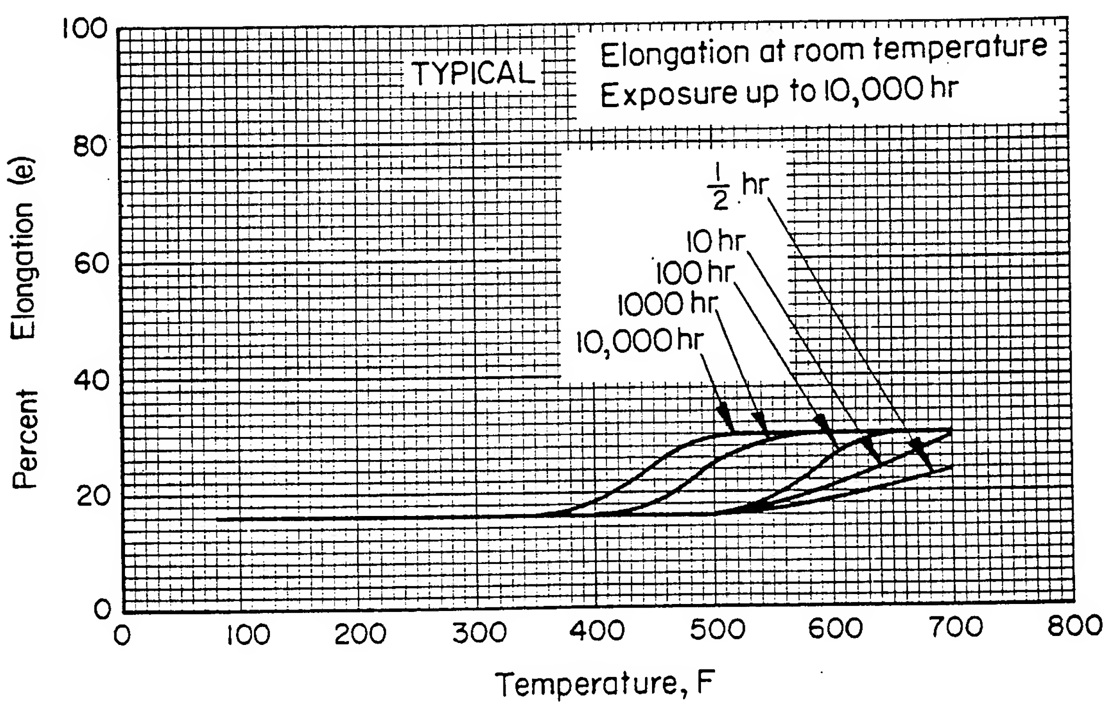

FIGURE 3.6.2.2.5(b). *Effect of exposure at elevated temperatures on the elongation of 6061-T6 aluminum alloy (all products).*

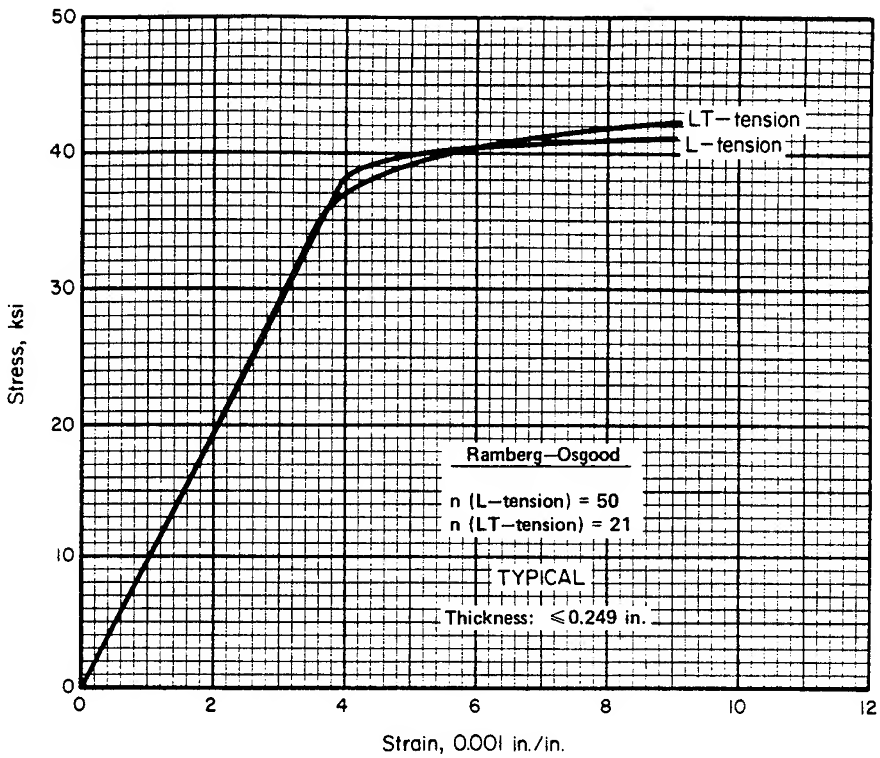

FIGURE 3.6.2.2.6(a). *Typical tensile stress-strain curves for 6061-T6 aluminum alloy sheet at room temperature.*

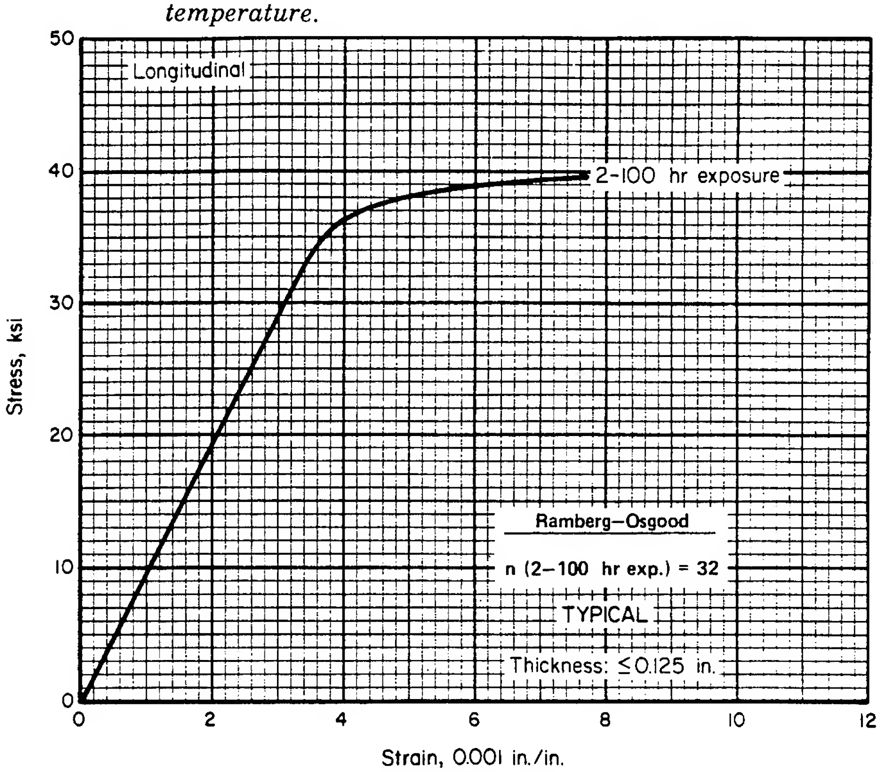

FIGURE 3.6.2.2.6(b). *Typical tensile stress-strain curve for 6061-T6 aluminum alloy sheet at 200 F.*

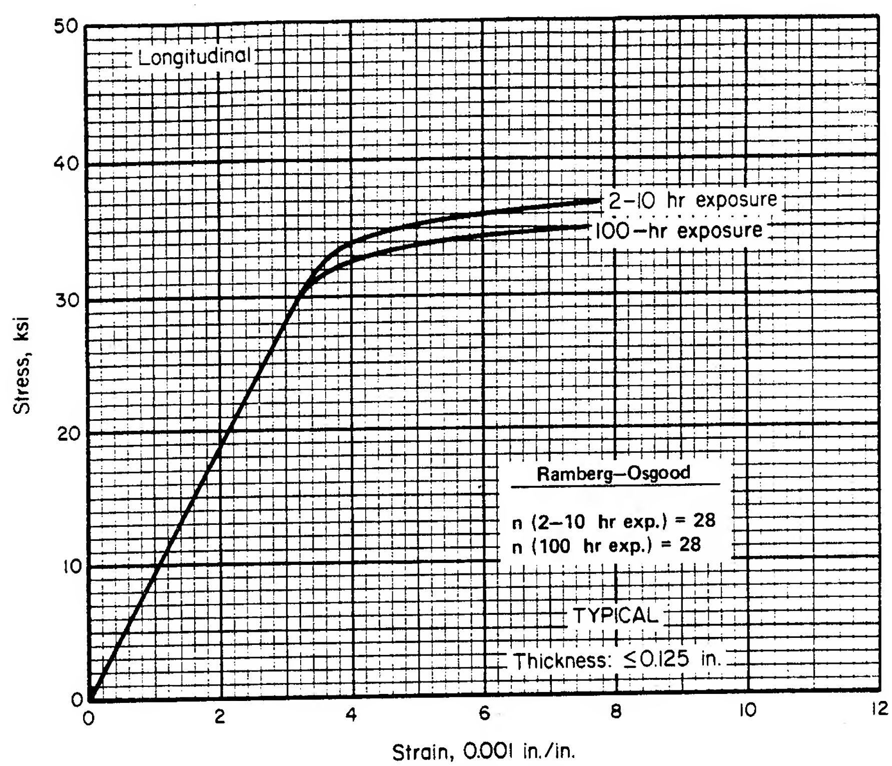

FIGURE 3.6.2.2.6(c). *Typical tensile stress-strain curves for 6061-T6 aluminum alloy sheet at 300 F.*

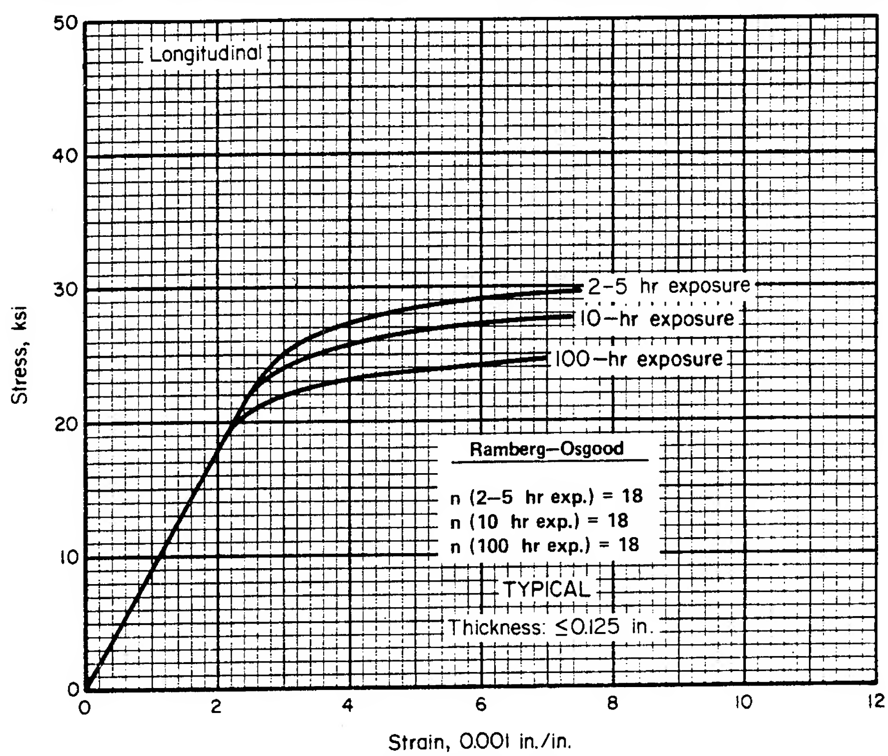

FIGURE 3.6.2.2.6(d). *Typical tensile stress-strain curves for 6061-T6 aluminum alloy sheet at 400 F.*

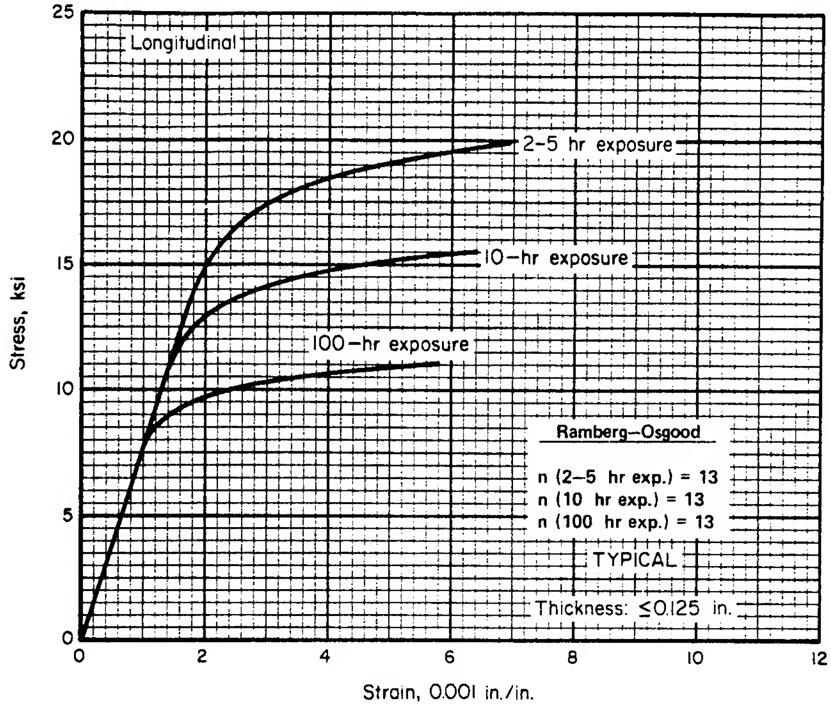

FIGURE 3.6.2.2.6(e). *Typical tensile stress-strain curves for 6061-T6 aluminum alloy sheet at 500 F.*

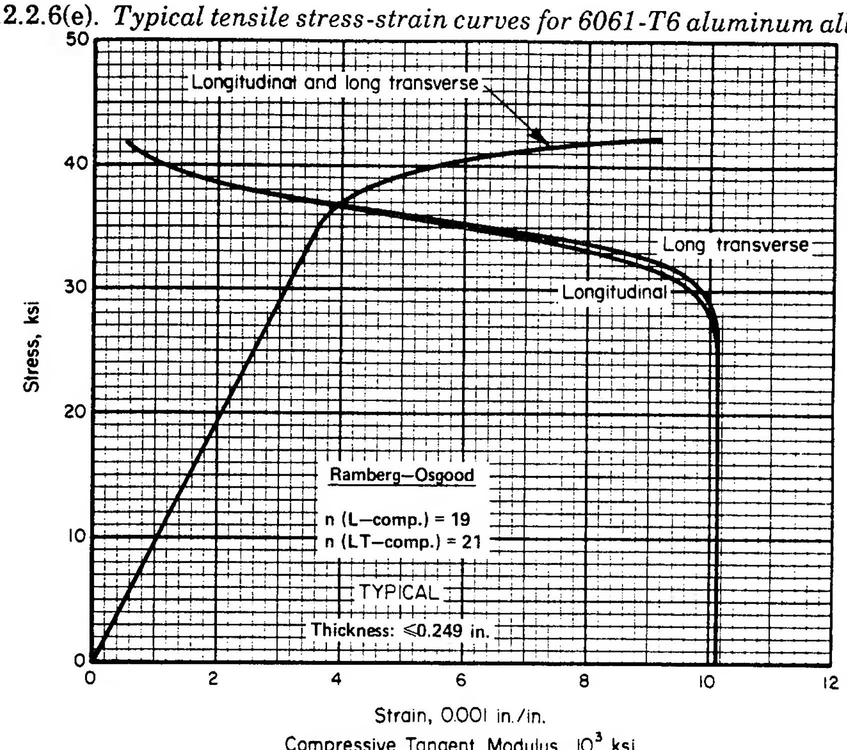

FIGURE 3.6.2.2.6(f). *Typical compressive stress-strain and compressive tangent-modulus curves for 6061-T6 aluminum alloy sheet at room temperature.*

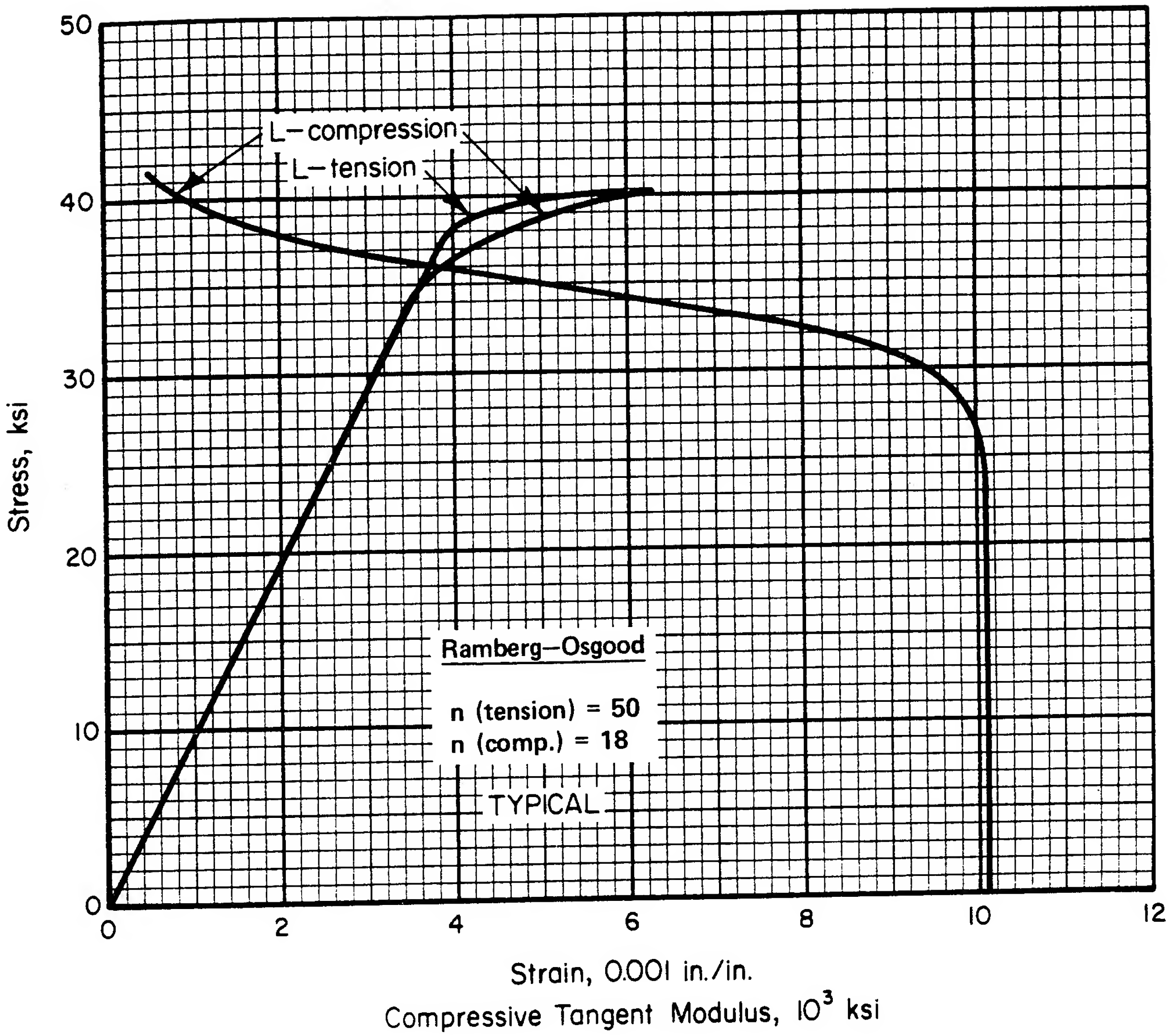

FIGURE 3.6.2.2.6(g). *Typical tensile and compressive stress-strain and compressive tangent-modulus curves for 6061-T6 aluminum alloy sheet at room temperature.*

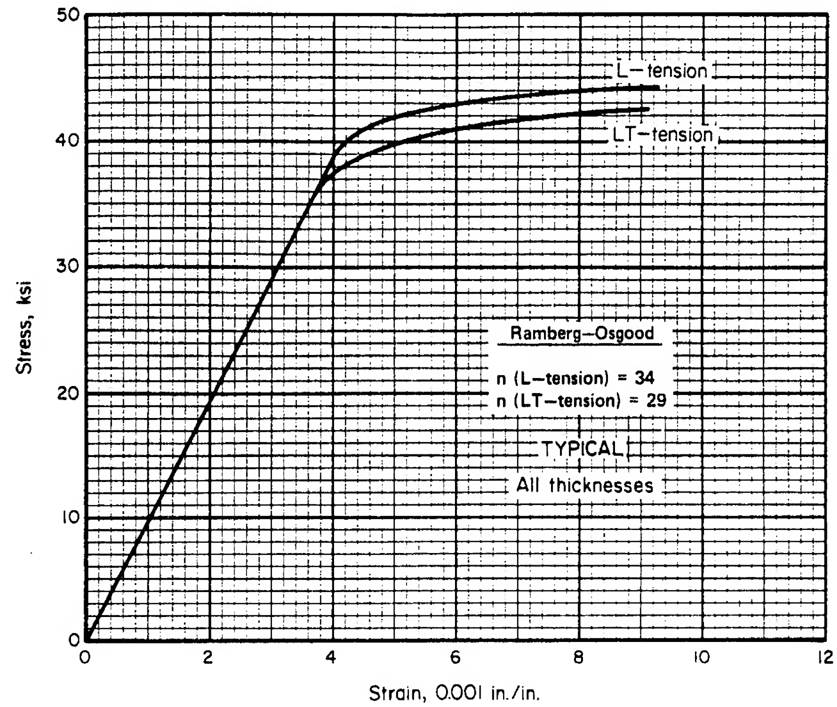

FIGURE 3.6.2.2.6(h). *Typical tensile stress-strain curves for 6061-T6 aluminum alloy extrusion at room temperature.*

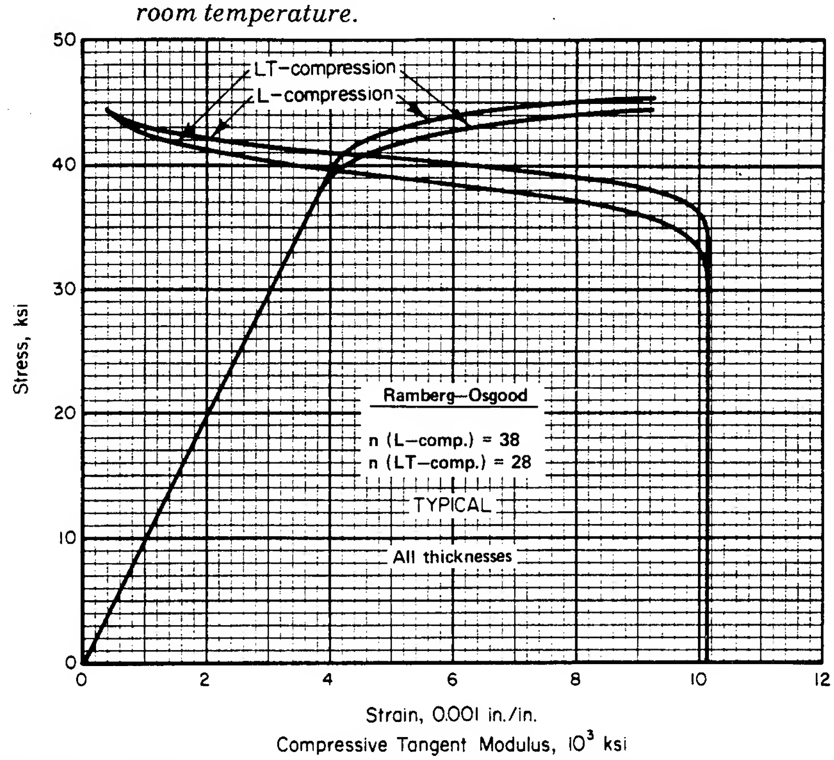

FIGURE 3.6.2.2.6(i). *Typical compressive stress-strain and compressive tangent-modulus curves for 6061-T6 aluminum alloy extrusion at room temperature.*

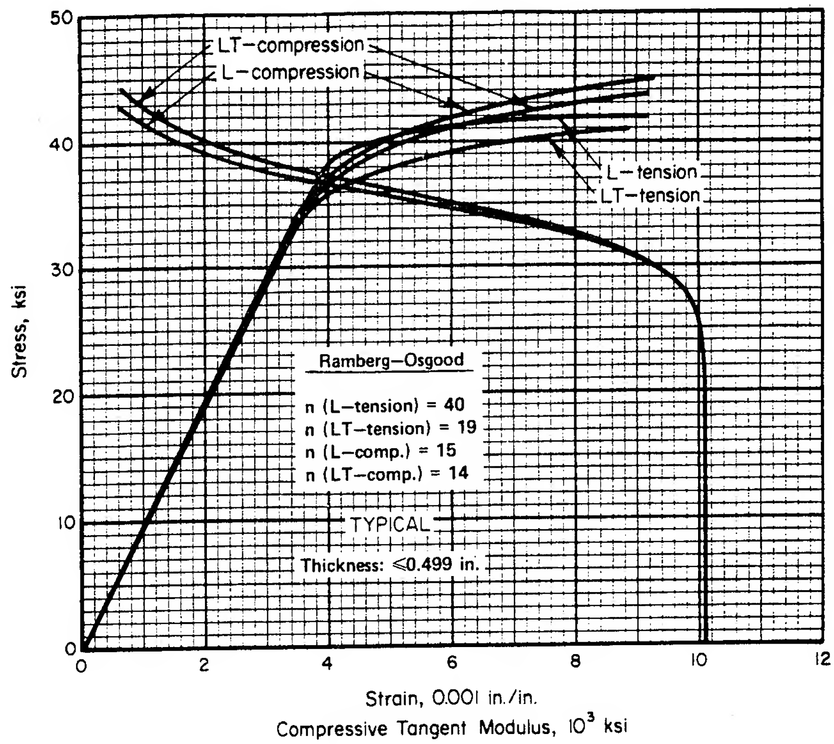

FIGURE 3.6.2.2.6(j). *Typical tensile and compressive stress-strain and compressive tangent-modulus curves for 6061-T651X aluminum alloy extrusion at room*

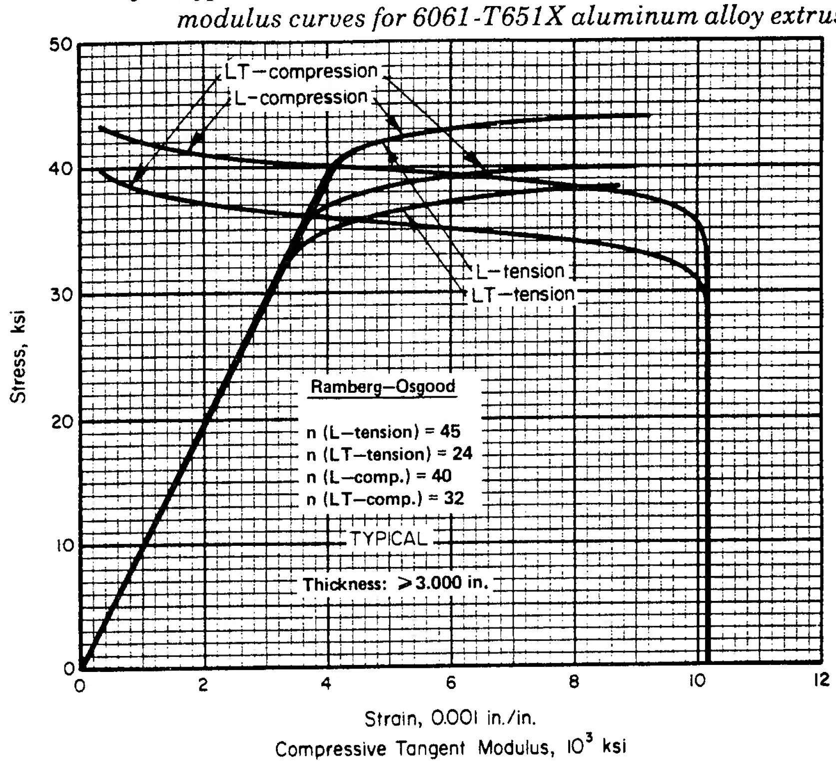

FIGURE 3.6.2.2.6(k). *Typical tensile and compressive stress-strain and compressive tangent-modulus curves for 6061-T651X aluminum alloy extrusion at room temperature.*

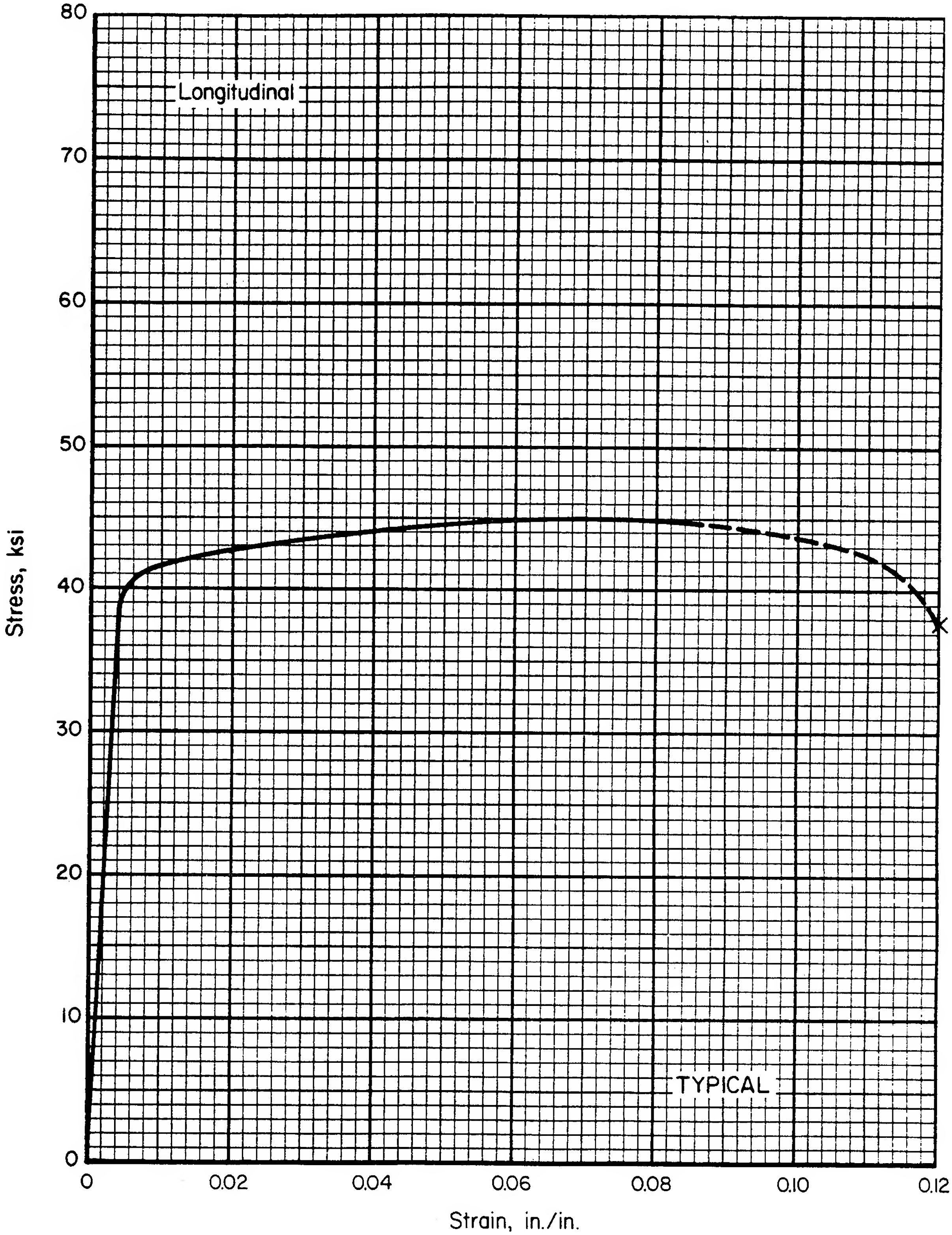

FIGURE 3.6.2.2.6(l). *Typical tensile stress-strain (full range) for 6061-T6 aluminum alloy sheet at room temperature.*

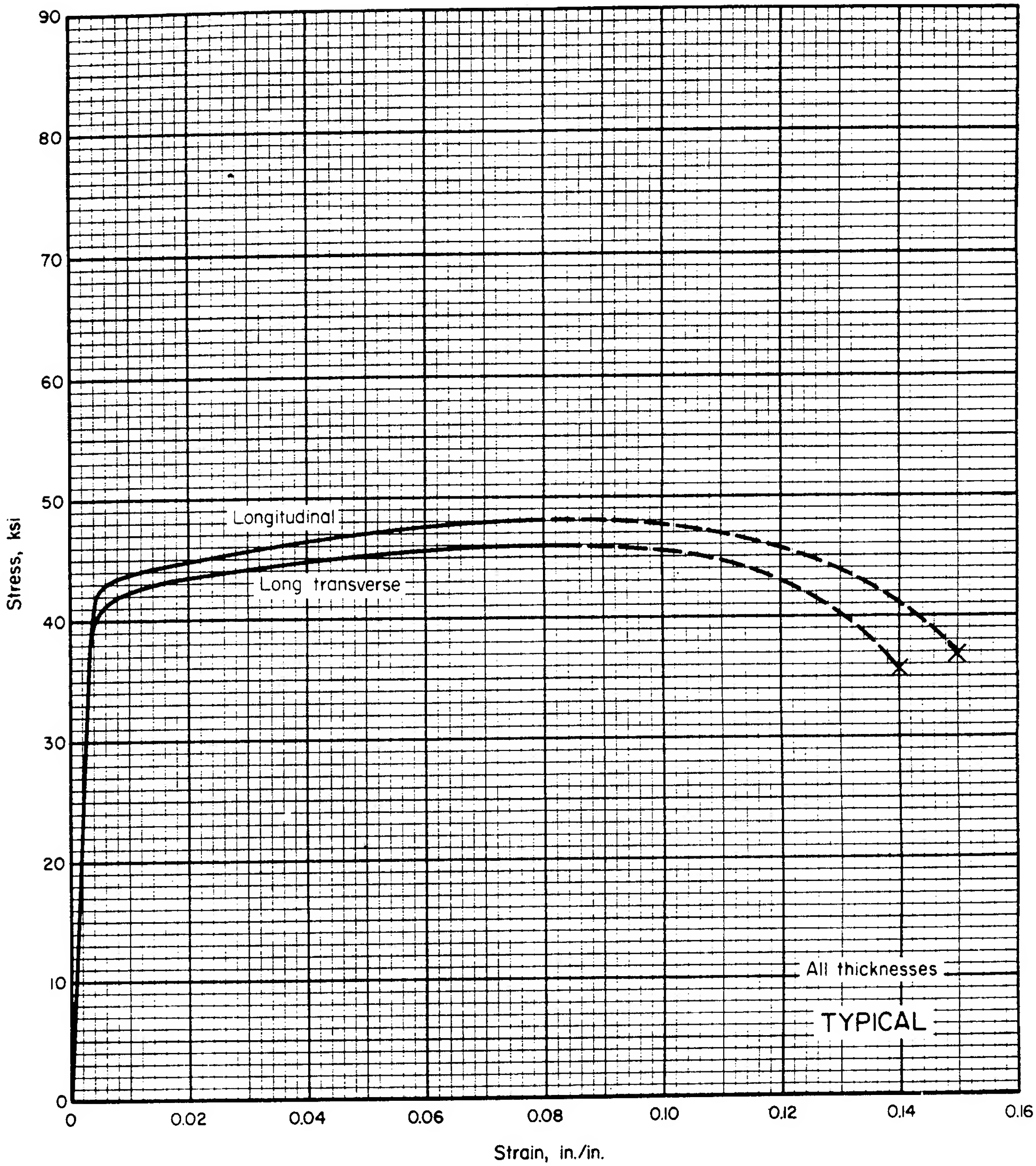

FIGURE 3.6.2.2.6(m). *Typical tensile stress-strain curves (full range) for 6061-T62 aluminum alloy extrusion at room temperature.*

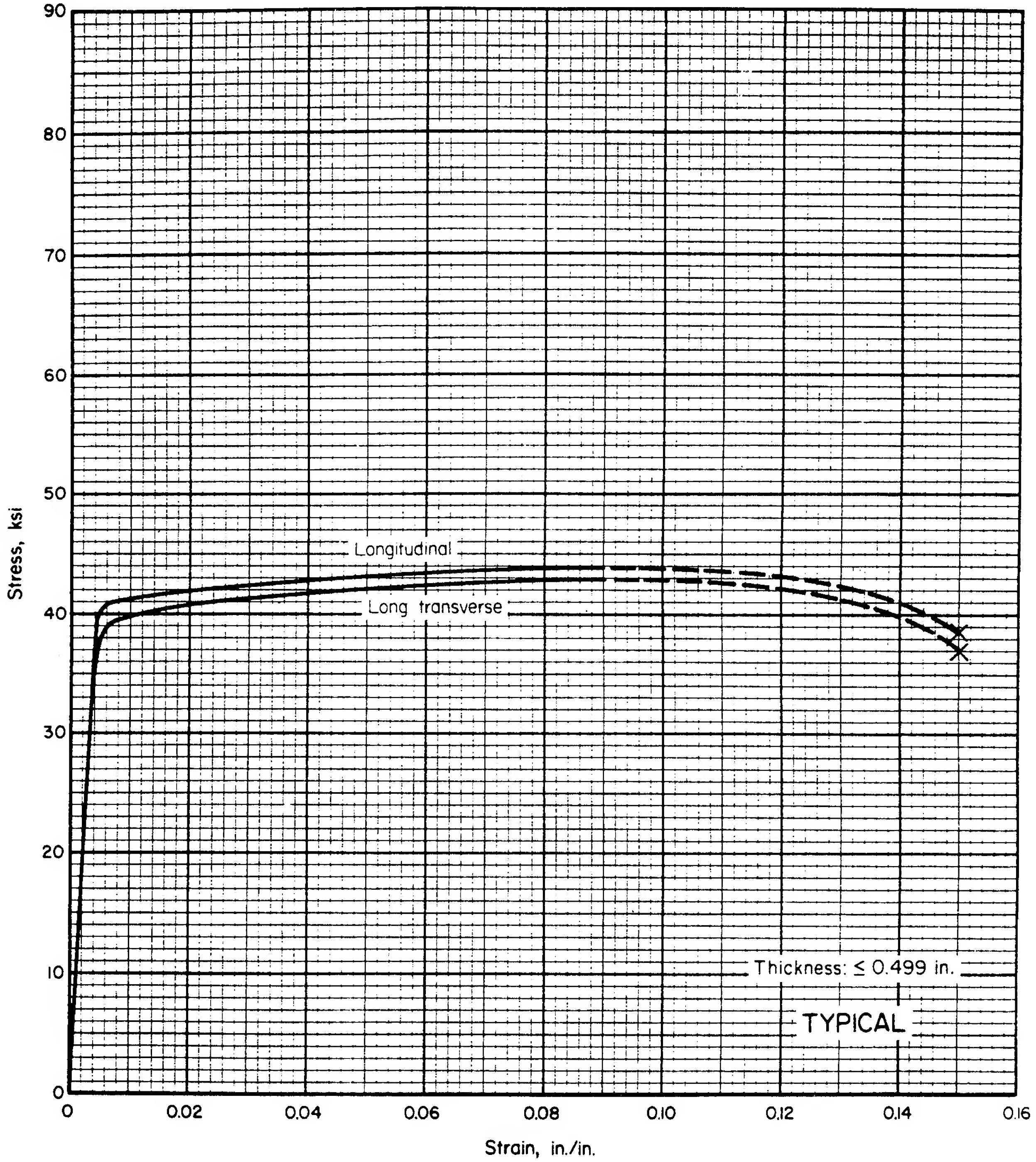

FIGURE 3.6.2.2.6(n). *Typical tensile stress-strain curves (full range) for 6061-T651X aluminum alloy extrusion at room temperature.*

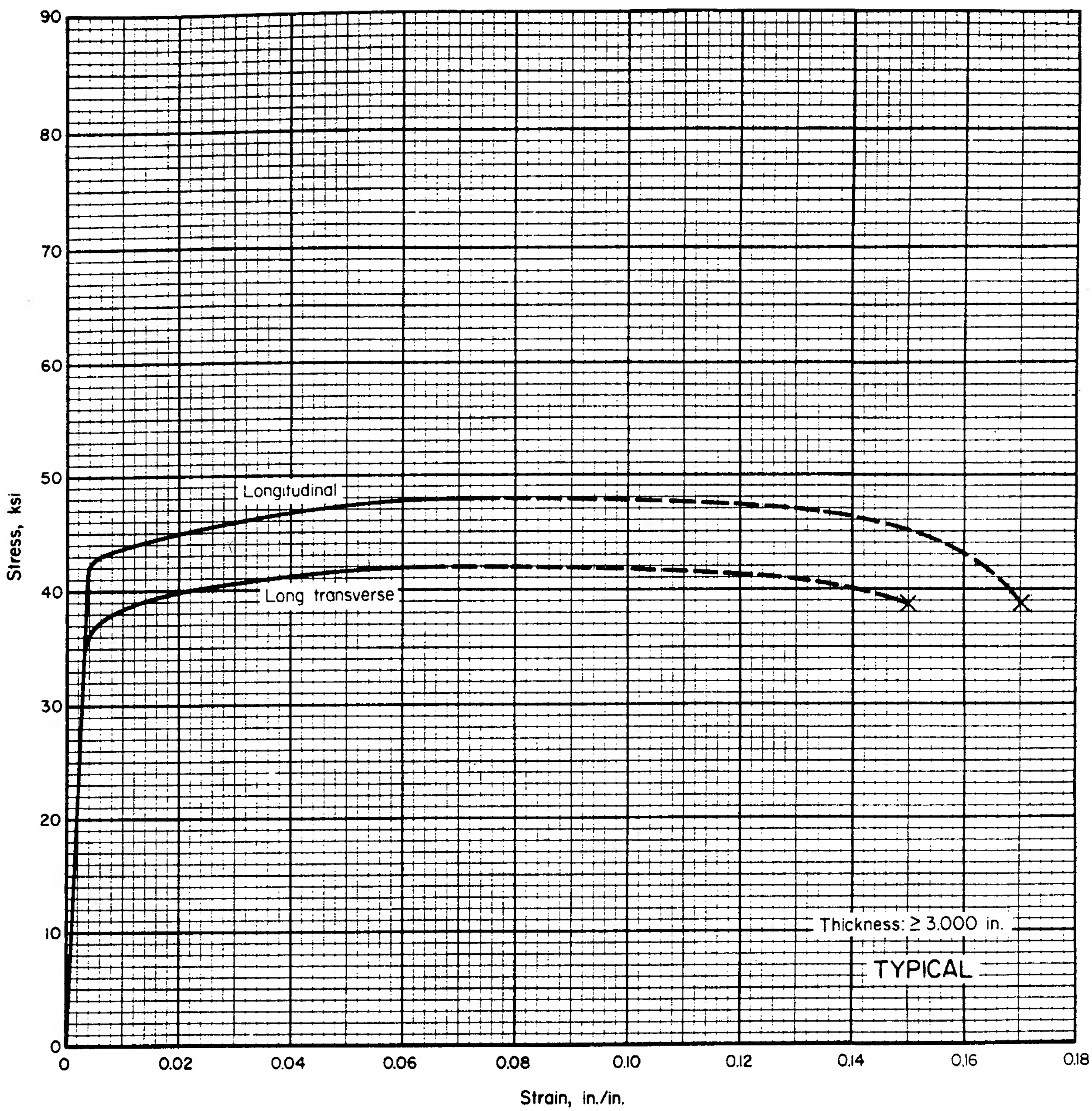

FIGURE 3.6.2.2.6(o). *Typical tensile stress-strain curves (full range) for 6061-T651X aluminum alloy extrusion at room temperature.*

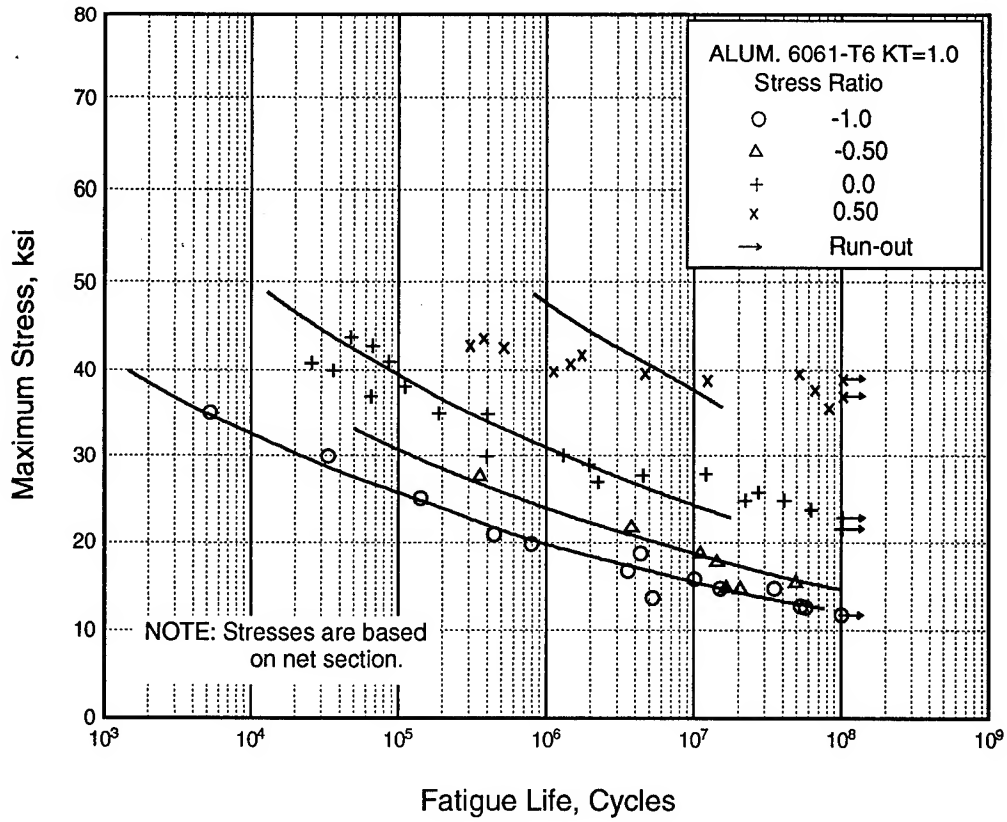

FIGURE 3.6.2.2.8. *Best-fit S/N curves for unnotched 6061-T6 aluminum alloy, various wrought products, longitudinal direction.*

Correlative Information for Figure 3.6.2.2.8

Product Form: Drawn rod, 3/4-inch diameter
Rolled bar, 1 x 7-1/2 inch

Properties:

TUS, ksi	TYS, ksi	Temp, F
45	40	RT

Specimen Details: Unnotched
0.200-inch net diameter

Surface Condition: Not specified

Reference: 3.2.1.1.8(a)

Test Parameters:

Loading - Axial
Frequency - 2000 cpm
Temperature - RT
Environment - Air

No. of Heats/Lots: Not specified

Equivalent Stress Equation:

Log N_f = 20.68-9.84 log (S_{eq})
$S_{eq} = S_{max}\,(1-R)^{0.63}$
Standard Error of Estimate = 0.48
Standard Deviation in Life = 1.18
R^2 = 83%

Sample Size: 55

[Caution: The equivalent stress model may provide unrealistic life predictions for stress ratios beyond those represented above.]

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3.6.3 6151 ALLOY

3.6.3.0 *Comments and Properties.*—6151 is an Al-Mg-Si alloy whose use has been restricted primarily to die forgings. It provides higher strengths than attainable with 6061, and has high resistance to corrosion. Refer to Section 3.1.3.4 for comments regarding the weldability of the alloy.

Material specifications for 6151 aluminum alloy are presented in Table 3.6.3.0(a). Room-temperature mechanical and physical properties are shown in Table 3.6.3.0(b). The effect of temperature on thermal expansion is shown in Figure 3.6.3.0.

TABLE 3.6.3.0(a). *Material Specifications for 6151 Aluminum Alloy*

Specification	Form
AMS 4125	Die forging
MIL-A-22771	Forging

The temper index for 6151 is as follows:

Section	Temper
3.6.3.1	T6

3.6.3.1 *T6 Temper.*—Elevated temperature modulus data from Figure 3.6.2.2.4 may be used for this alloy.

TABLE 3.6.3.0(b). *Design Mechanical and Physical Properties of 6151 Aluminum Alloy Die Forging*

Specification	AMS 4125 and MIL-A-22771
Form	Die forging
Temper	T6
Thickness[b], in.	≤4.000
Basis	S
Mechanical Properties:	
F_{tu}, ksi:	
L	44
T[a]	44
F_{ty}, ksi:	
L	37
T[a]	37
F_{cy}, ksi:	
L	39
T[a]	35
F_{su}, ksi	28
F_{bru}, ksi:	
(e/D = 1.5)	...
(e/D = 2.0)	...
F_{bry}, ksi:	
(e/D = 1.5)	...
(e/D = 2.0)	...
e, percent:	
L	10
T[a]	6
E, 10^3 ksi	10.1
E_c, 10^3 ksi	10.3
G, 10^3 ksi	3.85
μ	0.33
Physical Properties:	
ω, lb/in.^{3}	0.098
C, Btu/(lb)(F)	0.23 (at 212 F)
K, Btu/[(hr)(ft^2)(F)/ft]	100 (at 77 F)
α, 10^{-6} in./in./F	See Figure 3.6.3.0

[a]For die forgings, T indicates any grain direction not within ±15° of being parallel to the forging flow lines. Specimens to test transverse properties should be located as close to the short transverse direction as possible.
[b]Thickness at the time of heat treatment. When die forgings are machined before heat treatment, the mechanical properties are applicable provided the as-forged thickness is not greater than twice the thickness at the time of heat treatment.

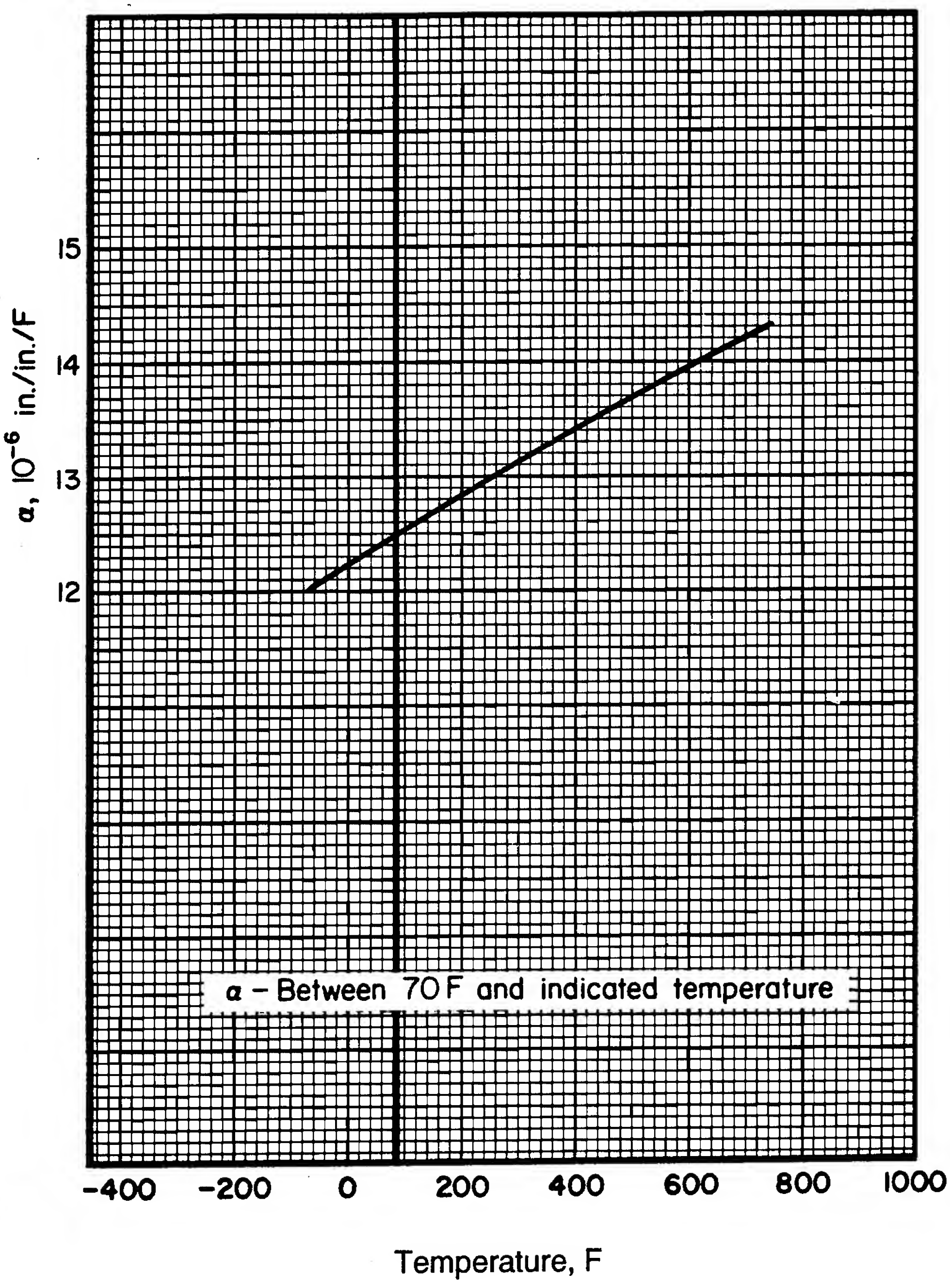


FIGURE 3.6.3.0. *Effect of temperature on the thermal expansion of 6151 aluminum alloy.*

3.7 7000 Series Wrought Alloys

The 7000 series of wrought alloys contain zinc as the principal alloying element and magnesium and copper as other major elements. They are available in a wide variety of product forms. They are strengthened principally by solution heat treatment and precipitation hardening, and are among the highest strength aluminum alloys.

The T6-type tempers of these alloys are susceptible to stress-corrosion cracking under certain conditions while the T7-type tempers are more resistant; these alloys should be considered in the light of Sections 3.1.2.3 and 3.1.3.

3.7.1 7010 ALLOY

3.7.1.0 *Comments and Properties.*—7010 is an Al-Zn-Mg-Cu-Zr alloy developed to have a combination of high strength, high resistance to stress-corrosion cracking, and good fracture toughness, particularly in thick sections. The use of zirconium in lieu of chromium provides a low sensitivity to quench, which results in high strength in thick sections. The alloy is available only in plate. Plate, greater than 2½ inches in thickness in the T7451 temper, has static strength equal to or greater than 7075-T651 plate with greater toughness.

Plate in the T7451 temper has a stress-corrosion resistance higher than 7075-T7651. The T73-type temper provides the highest resistance to stress-corrosion for this alloy. The T76-type temper provides for good exfoliation resistance and higher stress-corrosion resistance than T6-type tempers of 7075 and 7178. The T74 type temper provides stress-corrosion and strength characteristics intermediate to those of T76 and T73. Refer to Section 3.1.2.3 for information regarding the resistance of the alloy to stress-corrosion cracking.

Refer to Section 3.1.3.4 for comments regarding the weldability of the alloy.

Material specifications for 7010 are shown in Table 3.7.1.0(a). Room-temperature mechanical properties are shown in Tables 3.7.1.0(b_1) and (b_2).

TABLE 3.7.1.0(a). *Material Specifications for 7010 Aluminum Alloy*

Specification	Form
AMS 4205	Plate
AMS 4204	Plate

The temper index for 7050 is as follows:

Section	Temper
3.7.1.1	T7451
3.7.1.2	T7651

3.7.1.1 *T7451 Temper.*—Elevated temperature curves for plate are presented in Figure 3.7.1.1.1. Figures 3.7.1.1.6(a) through (d) present stress-strain and tangent-modulus curves for plate.

3.7.1.2 *T7651 Temper.*—Figures 3.7.1.2.6(a) through (d) present stress-strain and tangent-modulus curves for plate.

TABLE 3.7.1.0(b_1). *Design Mechanical and Physical Properties of 7010 Aluminum Alloy Plate*

Specification	AMS 4205									
Form	Plate									
Temper	T7451									
Thickness, in.	0.250-1.000	1.001-2.000	2.001-3.000		3.001-4.000		4.001-5.000		5.001-6.000	
Basis	S	S	A	B	A	B	A	B	A	B
Mechanical Properties:										
F_{tu}, ksi:										
L	71	71	70	72	70	71	68	71	68[b]	70
LT	72	72	71	72	70	72	69[b]	71	67[b]	71
ST	...	...	66	68	66	68	65[b]	67	63[b]	67
F_{ty}, ksi:										
L	62	62	60	62	60	62	59	61	57[b]	61
LT	62	62	60	62	59	61	58	60	57[b]	60
ST	...	...	55	57	54	56	53	55	52	54
F_{cy}, ksi:										
L	61	61	59	61	58	60	57	59	56	59
LT	63	63	62	64	61	63	60	62	59	63
ST	...	...	61	63	60	62	59	61	58	61
F_{su}, ksi	41	41	42	42	42	43	42	43	41	43
F_{bru}[a], ksi:										
(e/D = 1.5)	100	101	101	102	100	103	100	103	97	103
(e/D = 2.0)	127	129	130	132	130	134	129	133	126	133
F_{bry}[a], ksi:										
(e/D = 1.5)	81	82	81	84	81	84	81	84	80	84
(e/D = 2.0)	94	97	97	100	98	101	98	101	97	102
e, percent (S-basis):										
L	9	9	9	...	9	...	9	...	8	...
LT	6	6	6	...	6	...	5	...	5	...
ST	...	...	2.5	...	2	...	2	...	2	...

E, 10^3 ksi	10.2
E_c, 10^3 ksi	10.6
G, 10^3 ksi	3.9
μ	0.33
Physical Properties:	
ω, lb/in.^{3}	0.102
C, Btu/(lb)(F)	0.21 (at 214 F)
K, Btu/[(hr)(ft^2)(F)/ft]	95 (at 99 F)
α, 10^{-6} in./in./F	13.0 (68-212 F)

[a]See Table 3.1.2.1.1. Bearing values are "dry pin" values per Section 1.4.7.1.
[b]A values are higher than S values as follows: for 4.001-5.000-inch thickness, F_{tu}(L) = 69, F_{tu}(LT) = 70, and F_{tu}(ST) = 66; for 5.001-6.000-inch thickness, F_{tu}(LT) = 69, F_{tu}(ST) = 65, F_{ty}(L) = 59, and F_{ty}(LT) = 58.

TABLE 3.7.1.0(b_2). *Design Mechanical Properties of 7010 Aluminum Alloy Plate—Continued*

Specification	AMS 4204						
Form	Plate						
Temper	T7651						
Thickness, in.	0.250-1.000	1.001-2.000	2.001-2.500	2.501-3.000	3.001-4.000	4.001-5.000	5.001-5.500
Basis	S	S	S	S	S	S	S
Mechanical Properties:							
F_{tu}, ksi:							
L	76	76	75	73	72	72	71
LT	76	76	75	74	73	72	72
ST	...	...	71	70	69	68	66
F_{ty}, ksi:							
L	66	66	65	64	64	63	62
LT	66	66	65	64	53	62	61
ST	...	...	59	58	56	55	53
F_{cy}, ksi:							
L	65	65	64	63	62	61	60
LT	67	68	67	67	66	65	64
ST	...	...	68	67	65	64	62
F_{su}, ksi	42	44	44	44	44	45	46
F_{bru}[a], ksi:							
(e/D = 1.5)	105	106	106	105	105	105	105
(e/D = 2.0)	135	137	137	136	135	134	134
F_{bry}[a], ksi:							
(e/D = 1.5)	85	86	87	87	86	86	86
(e/D = 2.0)	103	104	103	102	101	100	99
e, percent:							
L	8	8	8	7	7	7	6
LT	6	6	6	5	5	5	4
ST	...	...	2.5	2.5	2	2	2
E, 10^3 ksi	10.2						
E_c, 10^3 ksi	10.6						
G, 10^3 ksi	3.9						
μ	0.33						
Physical Properties:							
ω, lb/in.^{3}	0.102						
C, Btu/(lb)(F)	0.21 (at 214 F)						
K, Btu/[(hr)(ft^2)(F)/ft]	95 (at 104 F)						
α, 10^{-6} in./in./F	12.9 (68 to 212 F)						

[a]See Table 3.1.2.1.1. Bearing values are "dry pin" values per Section 1.4.7.1.

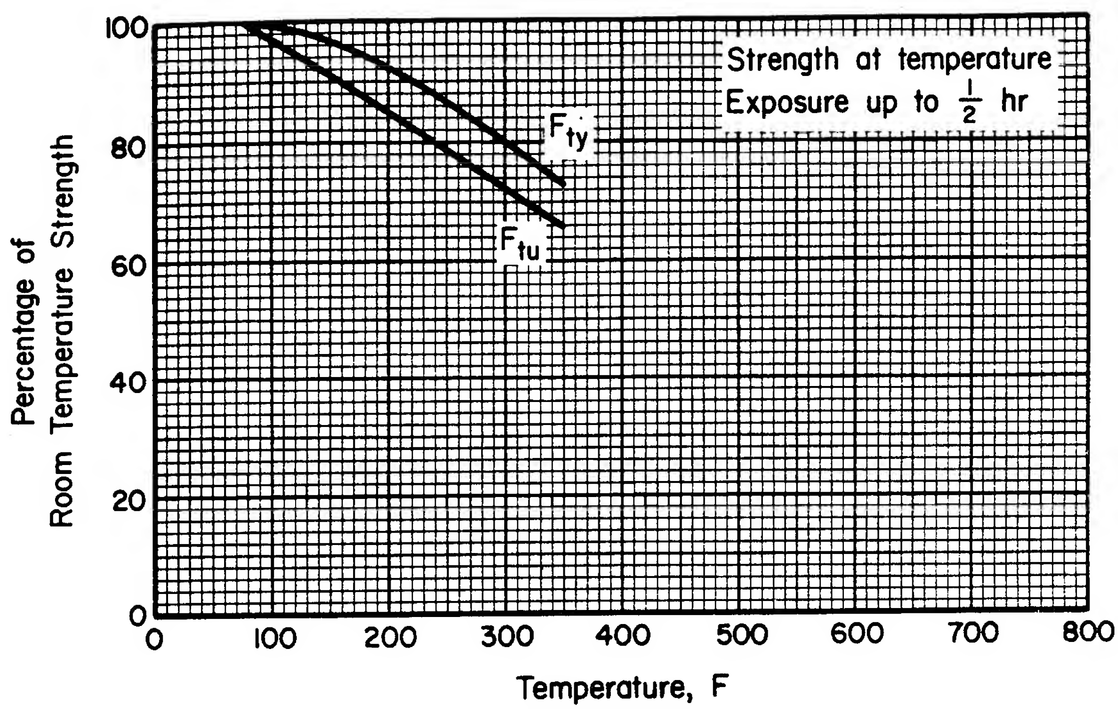


FIGURE 3.7.1.1.1. *Effect of temperature on the tensile ultimate strength (F_{tu}) and the tensile yield strength (F_{ty}) of 7010-T7451 aluminum alloy plate.*

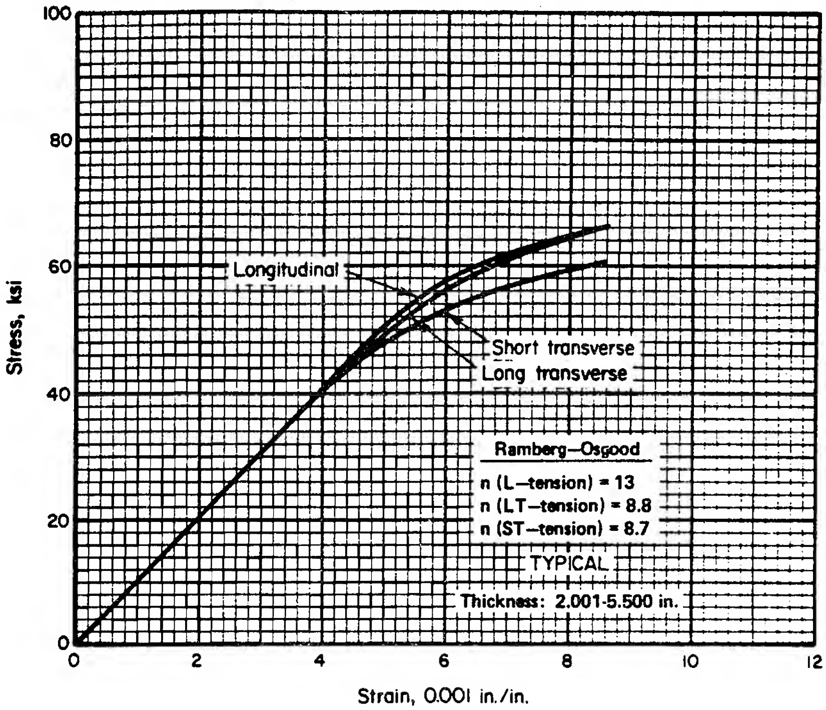


FIGURE 3.7.1.1.6(a). *Typical tensile stress-strain curves for 7010-T7451 plate at room temperature.*

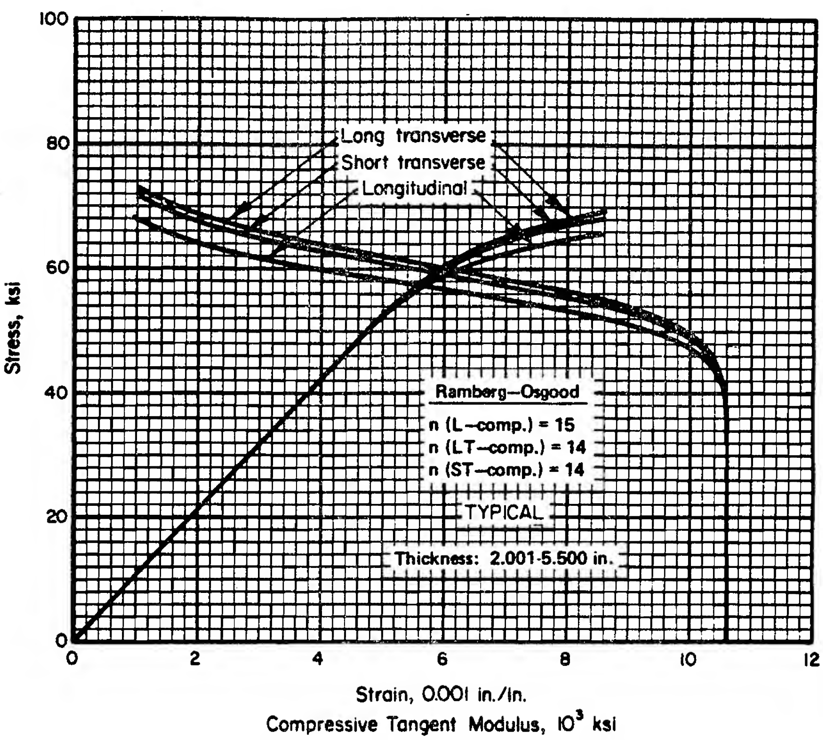


FIGURE 3.7.1.1.6(b). *Typical compressive stress-strain and compressive tangent-modulus curves for 7010-T7451 plate at room temperature.*

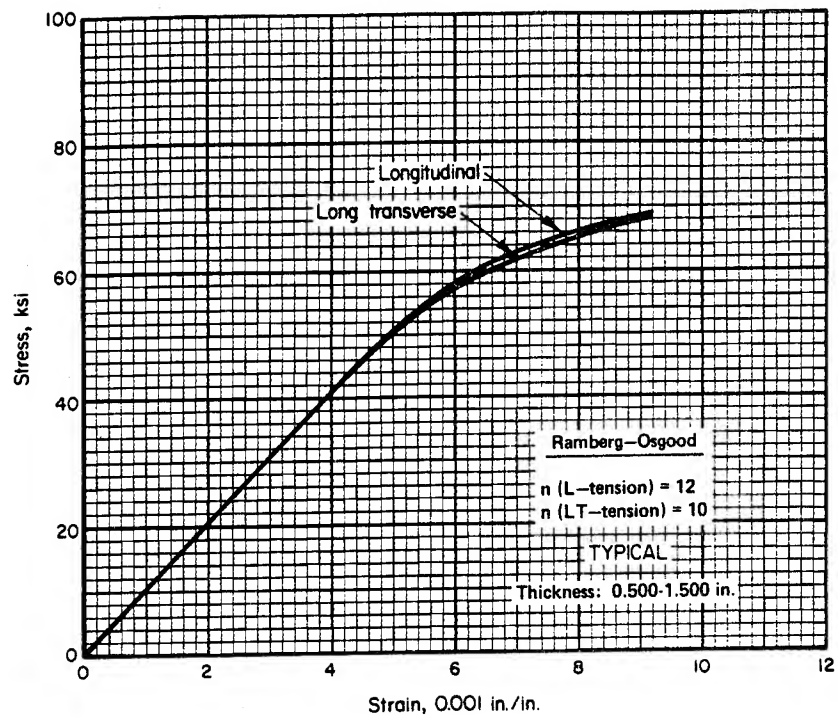


FIGURE 3.7.1.1.6(c). *Typical tensile stress-strain curves for 7010-T7451 aluminum alloy plate at room temperature.*

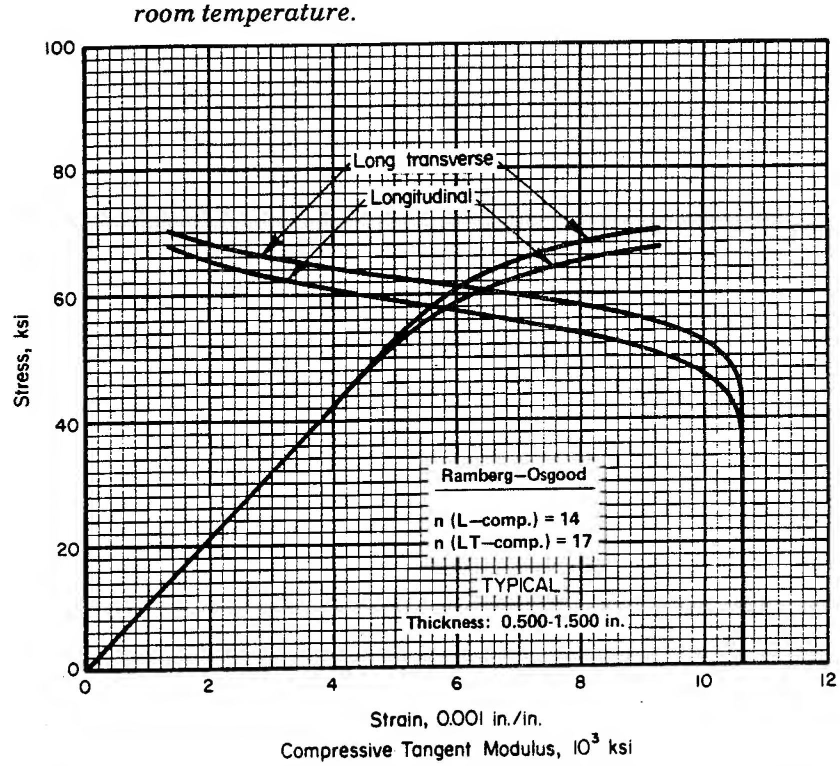


FIGURE 3.7.1.1.6(d). *Typical compressive stress-strain and compressive tangent-modulus curves for 7010-T7451 aluminum alloy plate at room temperature.*

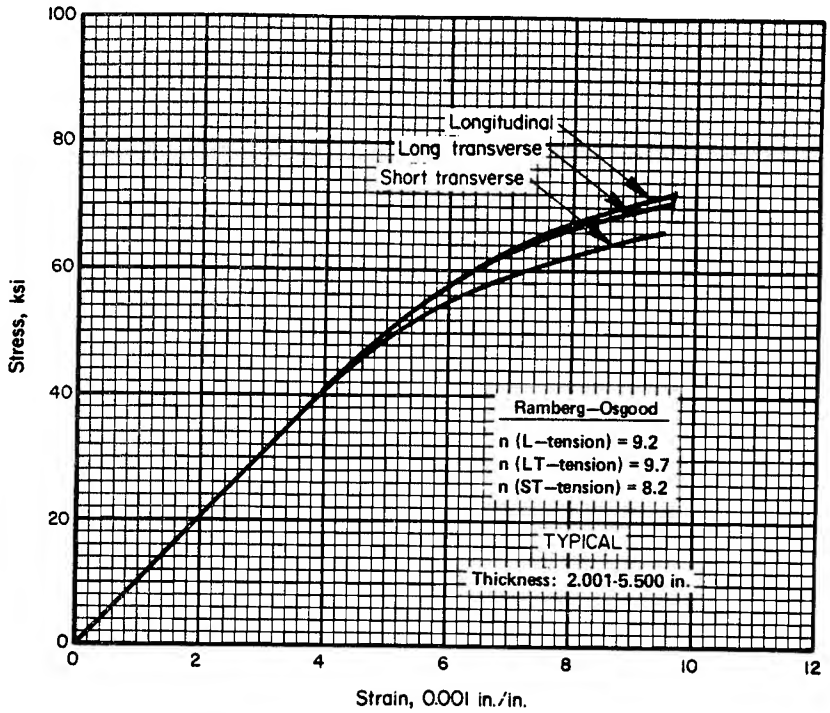


FIGURE 3.7.1.2.6(a). *Typical tensile stress-strain curves for 7010-T7651 plate at room temperature.*

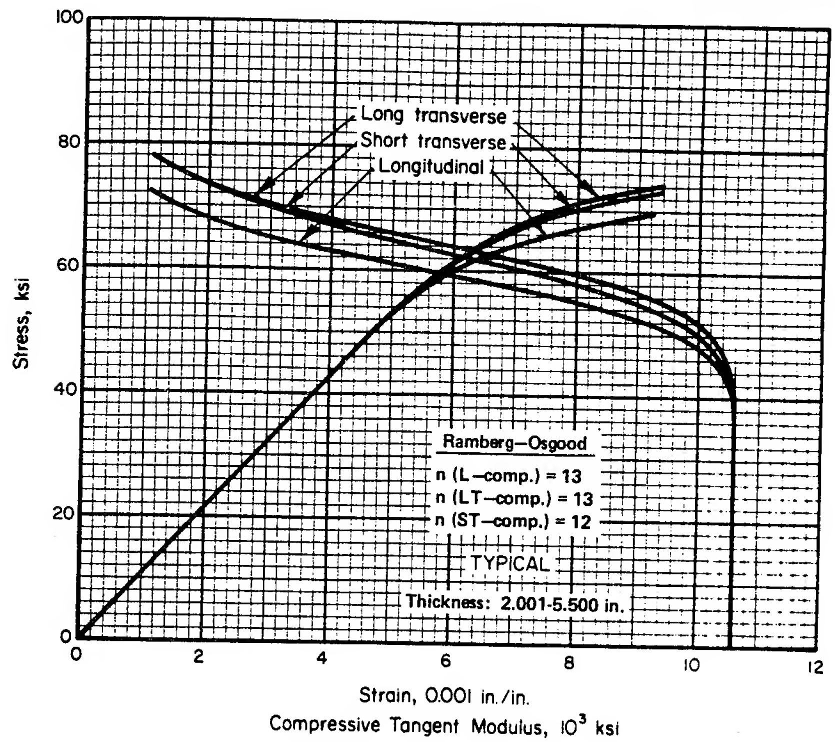


FIGURE 3.7.1.2.6(b). *Typical compressive stress-strain and compressive tangent-modulus curves for 7010-T7651 plate at room temperature.*

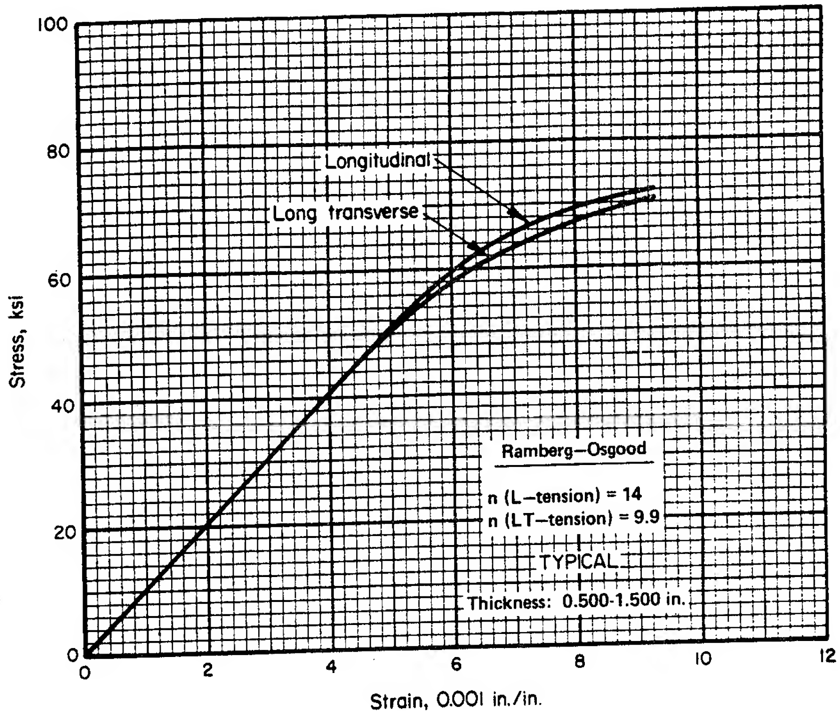


FIGURE 3.7.1.2.6(c). *Typical tensile stress-strain curves for 7010-T7651 aluminum alloy plate at room temperature.*

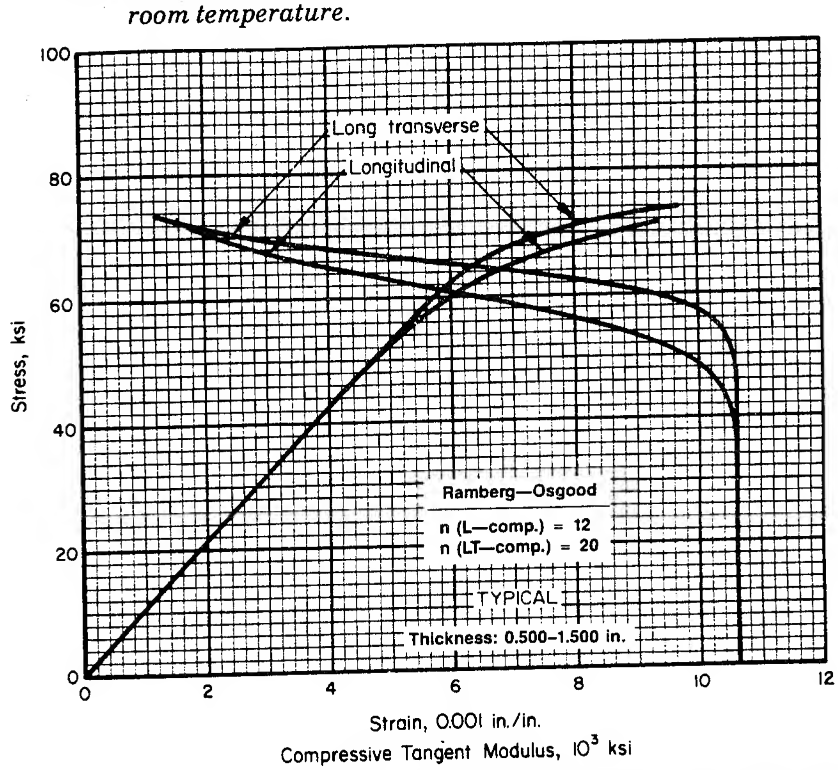


FIGURE 3.7.1.2.6(d). *Typical compressive stress-strain and compressive tangent-modulus curves for 7010-T7651 aluminum alloy plate at room temperature.*

3.7.2 7049/7149 ALLOY

3.7.2.0 *Comments and Properties.*—Alloy 7049/7149 is available in the form of die forging, hand forging, plate, and extrusion. Alloy 7149 contains lower residual iron and silicon content than 7049. The T73XX temper provides good static strength with high resistance to stress-corrosion cracking. The fatigue strength of the T73XX temper is about equal to that of 7075-T6, while the toughness is somewhat higher. Refer to Section 3.1.2.3 for comments regarding the resistance of the alloys to stress-corrosion cracking, and to Section 3.1.3.4 for comments regarding the weldability of the alloys.

Material specifications for 7049/7149 aluminum alloy are presented in Table 3.7.2.0(a). Room-temperature mechanical and physical properties are shown in Tables 3.7.2.0(b) through (e).

TABLE 3.7.2.0(a). *Material Specifications for 7049/7149 Aluminum Alloy*

Specification	Form
QQ-A-367 (7049)	Forging
AMS 4111 (7049)	Forging
AMS 4320 (7149)	Forging
AMS 4157 (7049)	Extrusion
MIL-A-22771	Forging
AMS 4200 (7049)	Plate
AMS 4343 (7149)	Extrusion

The temper index for 7049/7149 is as follows:

Section	Temper
3.7.2.1	T73 and T73511

3.7.2.1 *T73 and T73511 Tempers.*—Figure 3.7.2.1.1 presents elevated temperature curves for various products. Figures 3.7.2.1.6(a) through (g) present tensile and compressive stress-strain and tangent-modulus curves. Fatigue data for 7049-T73 die and hand forgings are shown in Figures 3.7.2.1.8(a) through (g).

TABLE 3.7.2.0(b). *Design Mechanical and Physical Properties of 7049 Aluminum Alloy Plate*

Specification	AMS 4200							
Form	Plate							
Temper	T7351							
Thickness, in.	0.750-1.000	1.001-1.500	1.501-2.000	2.001-2.500	2.501-3.000	3.001-4.000	4.001-4.500	4.501-5.000
Basis	S	S	S	S	S	S	S	S
Mechanical Properties:								
F_{tu}, ksi:								
L	...	...	72	72	71	70	68	68
LT	74	73	73	73	72	70	68	68
ST	...	...	69	69	68	65	63	63
F_{ty}, ksi:								
L	...	...	64	63	62	60	58	58
LT	65	64	64	63	62	60	58	58
ST	...	...	59	58	57	56	54	54
F_{cy}, ksi:								
L	...	...	64	63	62	60	58	...
LT	...	...	69	68	67	64	62	...
ST	...	...	69	68	67	64	62	...
F_{su}, ksi	...	...	41	41	41	39	38	...
F_{bru}[a], ksi:								
(e/D = 1.5)	...	...	...	114	112	109	106	...
(e/D = 2.0)	...	...	...	146	144	140	136	...
F_{bry}[a], ksi:								
(e/D = 1.5)	...	...	...	91	89	86	83	...
(e/D = 2.0)	...	...	...	106	104	101	97	...
e, percent:								
L	...	...	...	...	...	6	6	5
LT	8	8	7	6	6	5	5	5
ST	...	...	...	...	...	2	2	2
E, 10^3 ksi	10.1							
E_c, 10^3 ksi	10.4							
G, 10^3 ksi	3.9							
μ	0.33							
Physical Properties:								
ω, lb/in.^{3}	0.102							
C, Btu/(lb)(F)	0.23 (at 212 F)							
K, Btu/[(hr)(ft^2)(F)/ft]	89 (at 77 F)							
α, 10^{-6} in./in./F	13.0 (RT to 212 F)							

[a]Bearing values are "dry pin" values per Section 1.4.7.1. See Table 3.1.2.1.1.

TABLE 3.7.2.0(c). *Design Mechanical and Physical Properties of 7049/7149 Aluminum Alloy Die Forging*

Specification	QQ-A-367, AMS 4111, AMS 4320, and MIL-A-22771									
Form	Die forging									
Temper	T73[a]									
Thickness[b], in.	≤1.000		1.001-2.000		2.001-3.000		3.001-4.000		4.001-5.000	
Basis	A	B	A	B	A	B	A	B	A	B
Mechanical Properties:										
F_{tu}, ksi:										
L	71	74	70	73	69	72	68	71	67	70
T[c]	71[e]	...	70[e]	...	70[e]	...	70[e]	...	68[e]	...
F_{ty}, ksi:										
L	60	64	59	63	58	61	57	60	55	59
T[c]	61[e]	...	60[e]	...	60[e]	...	60[e]	...	58[e]	...
F_{cy}, ksi:										
L	62	66	61	65	60	63	59	62	57	61
ST	56	60	55	59	54	57	53	56	51	55
F_{su}, ksi	40	41	39	41	39	40	38	40	37	39
F_{bru}[d], ksi:										
(e/D = 1.5)	100	105	99	103	98	102	96	100	95	99
(e/D = 2.0)	132	138	130	136	128	134	126	132	125	130
F_{bry}[d], ksi:										
(e/D = 1.5)	76	82	75	80	74	78	73	76	70	75
(e/D = 2.0)	93	99	91	97	90	94	88	93	85	91
e, percent (S-basis):										
L	7	...	7	...	7	...	7	...	7	...
T[c]	3	...	3	...	3	...	2	...	2	...
E, 10^3 ksi	10.2									
E_c, 10^3 ksi	10.7									
G, 10^3 ksi	3.9									
μ	0.33									
Physical Properties:										
ω, lb/in.^{3}	0.102									
C, Btu/(lb)(F)	0.25 (at 212 F)									
K, Btu/[(hr)(ft^2)(F)/ft]	89 (at 77 F)									
α, 10^{-6} in./in./F	13.0 (RT to 212 F)									

[a] Design values were based upon data obtained from testing T73 die forgings, heat treated by suppliers and supplied in T73 temper.
[b] Thickness at the time of heat treatment. When die forgings are machined before heat treatment, the mechanical properties are applicable provided the as-forged thickness is not greater than twice the thickness at the time of heat treatment.
[c] For die forgings, T indicates any grain direction not within ±15° of being parallel to the forging flow lines. Specimens to test transverse properties should be located as close to the short transverse direction as possible.
[d] Bearing values are "dry pin" values per Section 1.4.7.1.
[e] Specification value. T tensile properties are presented on an S-basis only.

TABLE 3.7.2.0(d). *Design Mechanical and Physical Properties of 7049/7149 Aluminum Alloy Hand Forging*

Specification	QQ-A-367, AMS 4111, AMS 4320, and MIL-A-22771		
Form	Hand forging		
Temper	T73		
Thickness[a], in.	2.001-3.000	3.001-4.000	4.001-5.000
Basis	S	S	S
Mechanical Properties:			
F_{tu}, ksi:			
L	71	69	67
LT	71	69	67
ST	69	67	66
F_{ty}, ksi:			
L	61	59	56
LT	59	57	56
ST	58	56	55
F_{cy}, ksi:			
L	60	58	57
LT	61	59	57
ST	61	59	58
F_{su}, ksi:			
L	42	41	39
LT	41	39	38
ST	41	40	39
F_{bru}[b], ksi:			
(e/D = 1.5)	102	100	97
(e/D = 2.0)	134	130	126
F_{bry}[b], ksi:			
(e/D = 1.5)	81	79	77
(e/D = 2.0)	96	92	91
e, percent:			
L	9	8	7
LT	4	3	3
ST	3	2	2
E, 10^3 ksi	10.2		
E_c, 10^3 ksi	10.6		
G, 10^3 ksi	3.9		
μ	0.33		
Physical Properties:			
ω, lb./in.^{3}	0.102		
C, Btu/(lb)(F)	0.23 (at 212 F)		
K, Btu/[(hr)(ft^2)(F)/ft]	89 (at 77 F)		
α, 10^{-6} in./in./F	13.0 (RT to 212 F)		

[a]When hand forgings are machined before heat treatment, section thickness at time of heat treatment shall determine minimum mechanical properties as long as original (as-forged) thickness does not exceed maximum thickness for the alloy as shown in the table. The maximum cross-section area of hand forgings is 256 sq. in.
[b]Bearing values are "dry pin" values per Section 1.4.7.1.

TABLE 3.7.2.0(e). *Design Mechanical and Physical Properties of 7049/7149 Aluminum Alloy Extrusion*

Specification	AMS 4157 and AMS 4343		
Form	Extrusion		
Temper	T73511		
Thickness, in.	≤ 2.499	2.500-2.999	3.000-5.000
Basis	S	S	S
Mechanical Properties:			
F_{tu}, ksi:			
L	74	74	72
LT	70	70	68
ST	...	70	68
F_{ty}, ksi:			
L	64	64	62
LT	60	60	58
ST	...	60	58
F_{cy}, ksi:			
L	65	65	63
LT	...	...	...
ST	...	...	...
F_{su}, ksi	40	40	39
F_{bru}[a], ksi:			
(e/D = 1.5)	110	110	107
(e/D = 2.0)	144	144	140
F_{bry}[a], ksi:			
(e/D = 1.5)	85	85	83
(e/D = 2.0)	105	105	101
e, percent:			
L	7	7	7
LT	5	5	5
ST	...	5	5
E, 10^3 ksi	10.5		
E_c, 10^3 ksi	11.0		
G, 10^3 ksi	4.0		
μ	0.33		
Physical Properties:			
ω, lb/in.^{3}	0.102		
C, Btu/(lb)(F)	0.23 (at 212 F)		
K, Btu/[(hr)(ft^2)(F)/ft]	89		
α, 10^{-6} in./in./F	13.0 (RT to 212 F)		

[a]Bearing values are "dry pin" values per Section 1.4.7.1.

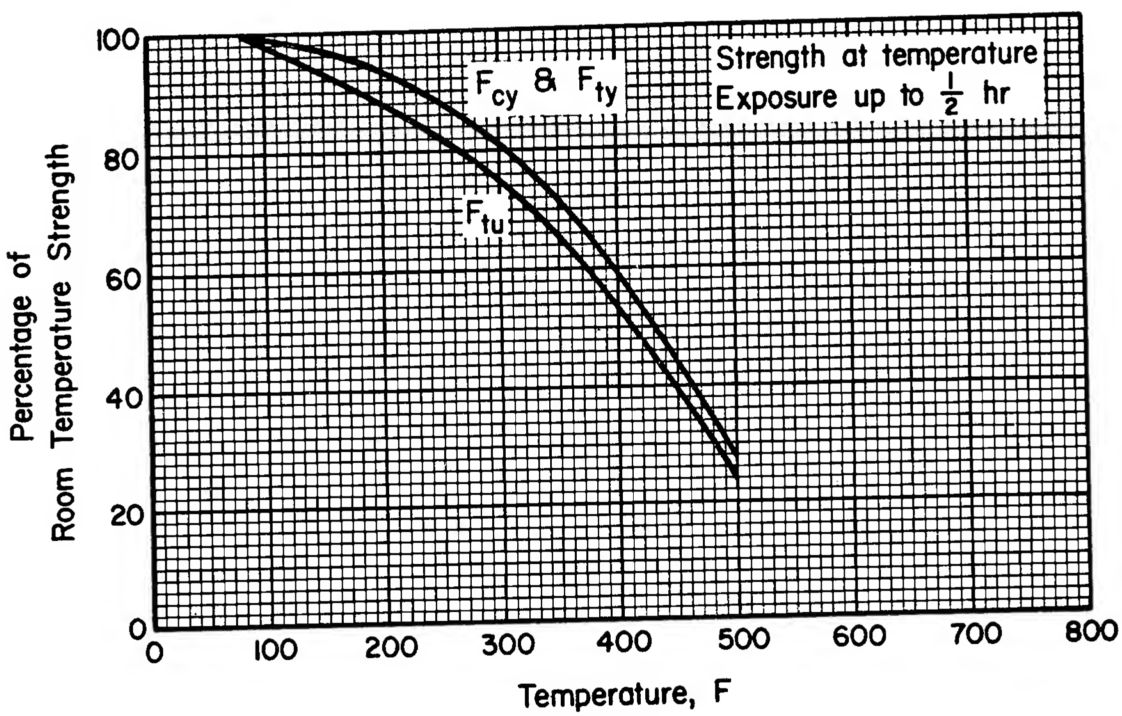


FIGURE 3.7.2.1.1. *Effect of temperature on the tensile ultimate strength (F_{tu}), the tensile yield strength (F_{ty}), and the compressive yield strength (F_{cy}) of 7049-T7351 plate, 7049/7149-T73 hand forging, and 7049/7149-T7351 extrusion.*

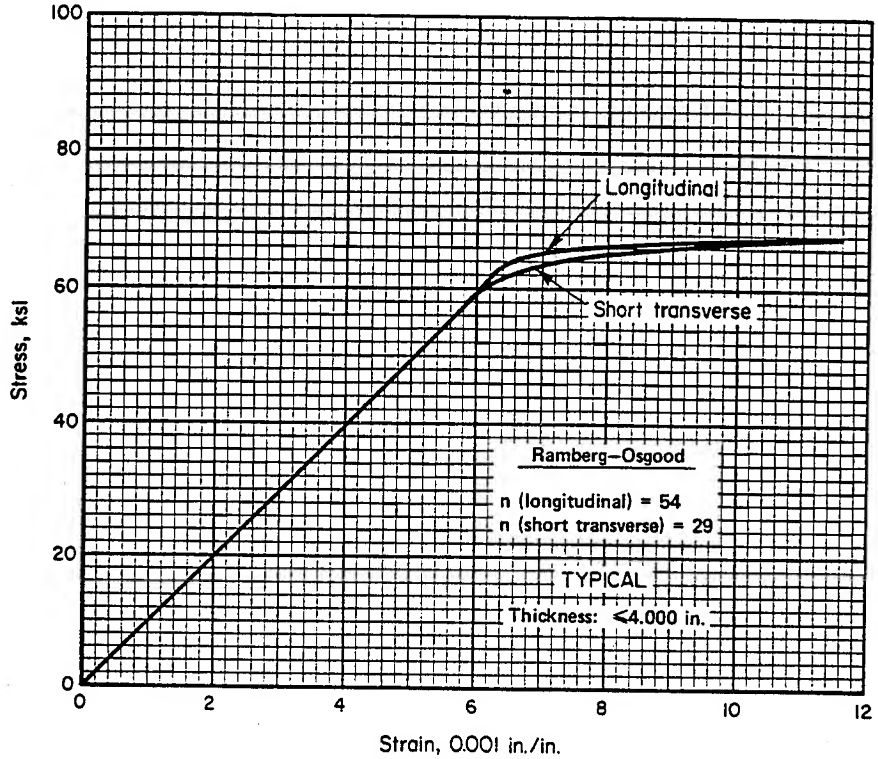


FIGURE 3.7.2.1.6(a). *Typical tensile stress-strain curves for 7049/7149-T73 aluminum alloy die forging at room temperature.*

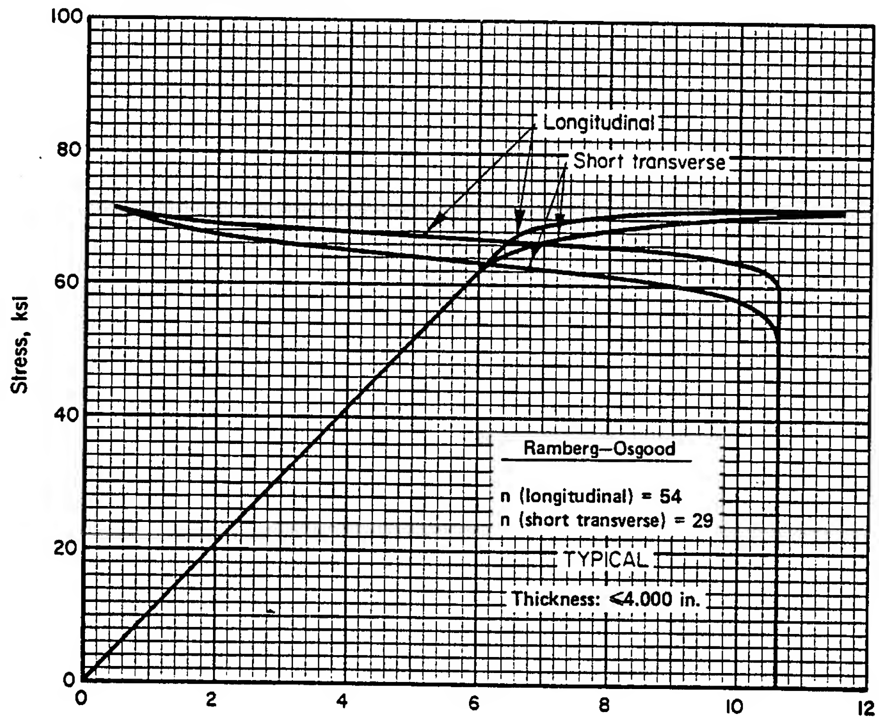


FIGURE 3.7.2.1.6(b). *Typical compressive stress-strain and compressive tangent-modulus curves for 7049/7149-T73 aluminum alloy die forging at room temperature.*

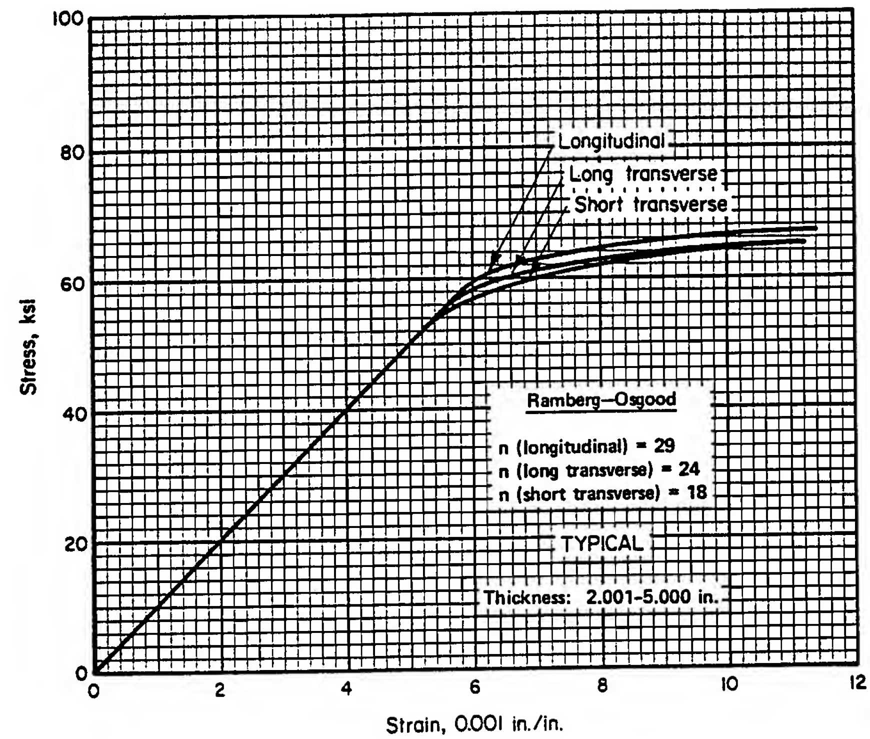


FIGURE 3.7.2.1.6(c). *Typical tensile stress-strain curves for 7049/7149-T73 aluminum alloy hand forging at room temperature.*

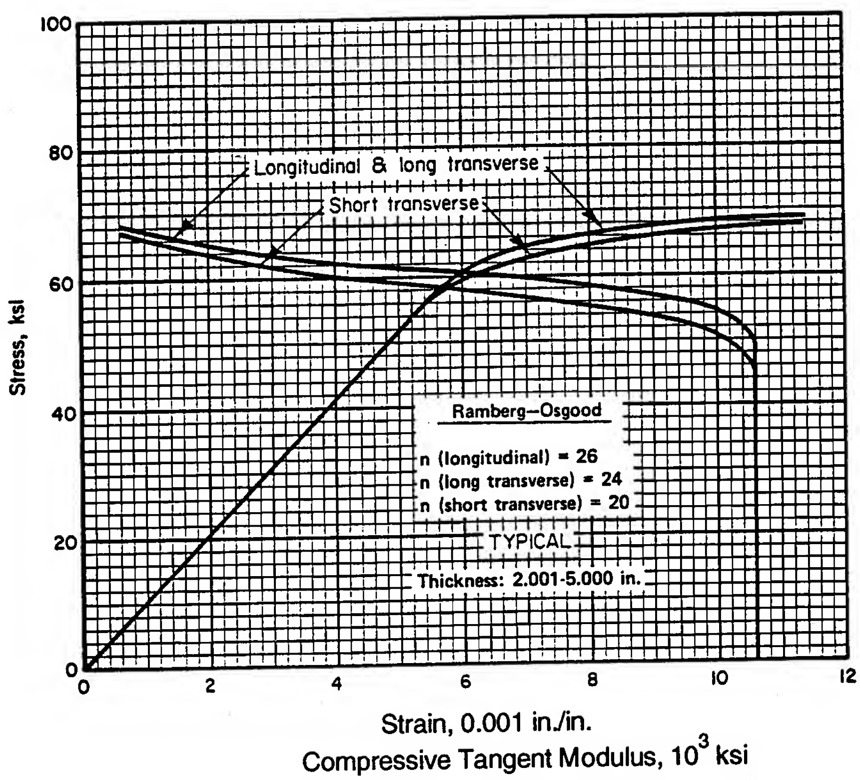


FIGURE 3.7.2.1.6(d). *Typical compressive stress-strain and compressive tangent-modulus curves for 7049/7149-T73 aluminum alloy hand forging at room temperature.*

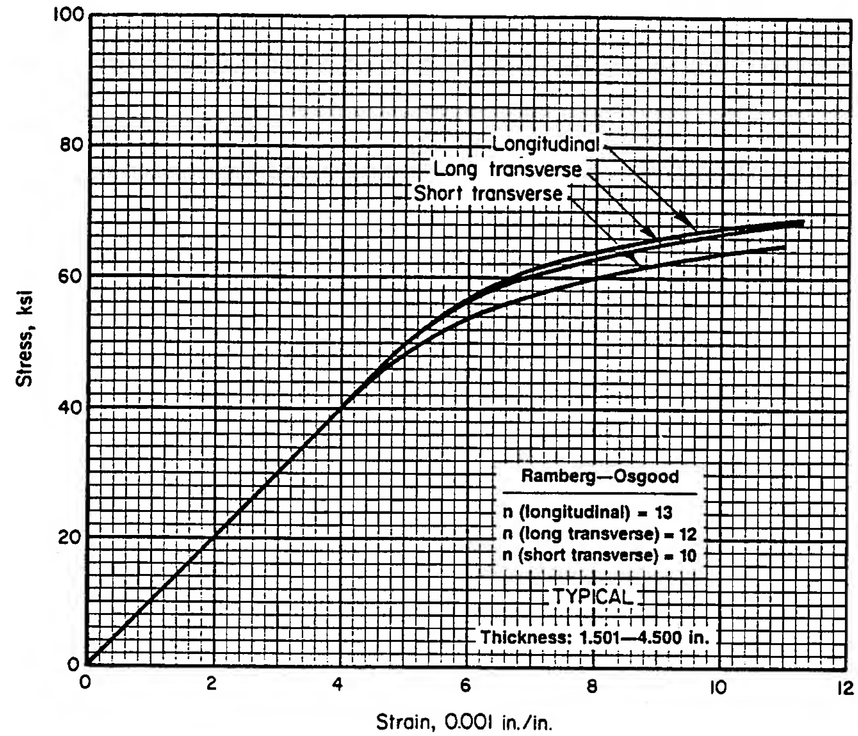
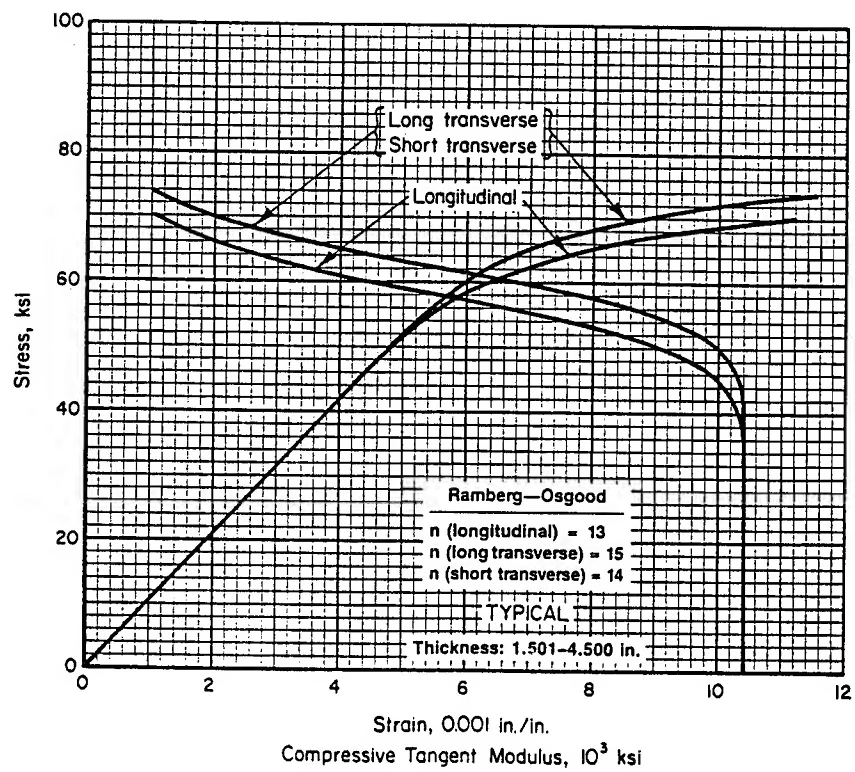


FIGURE 3.7.2.1.6(e). *Typical tensile stress-strain curves for 7049-T7351 aluminum alloy plate at room temperature.*



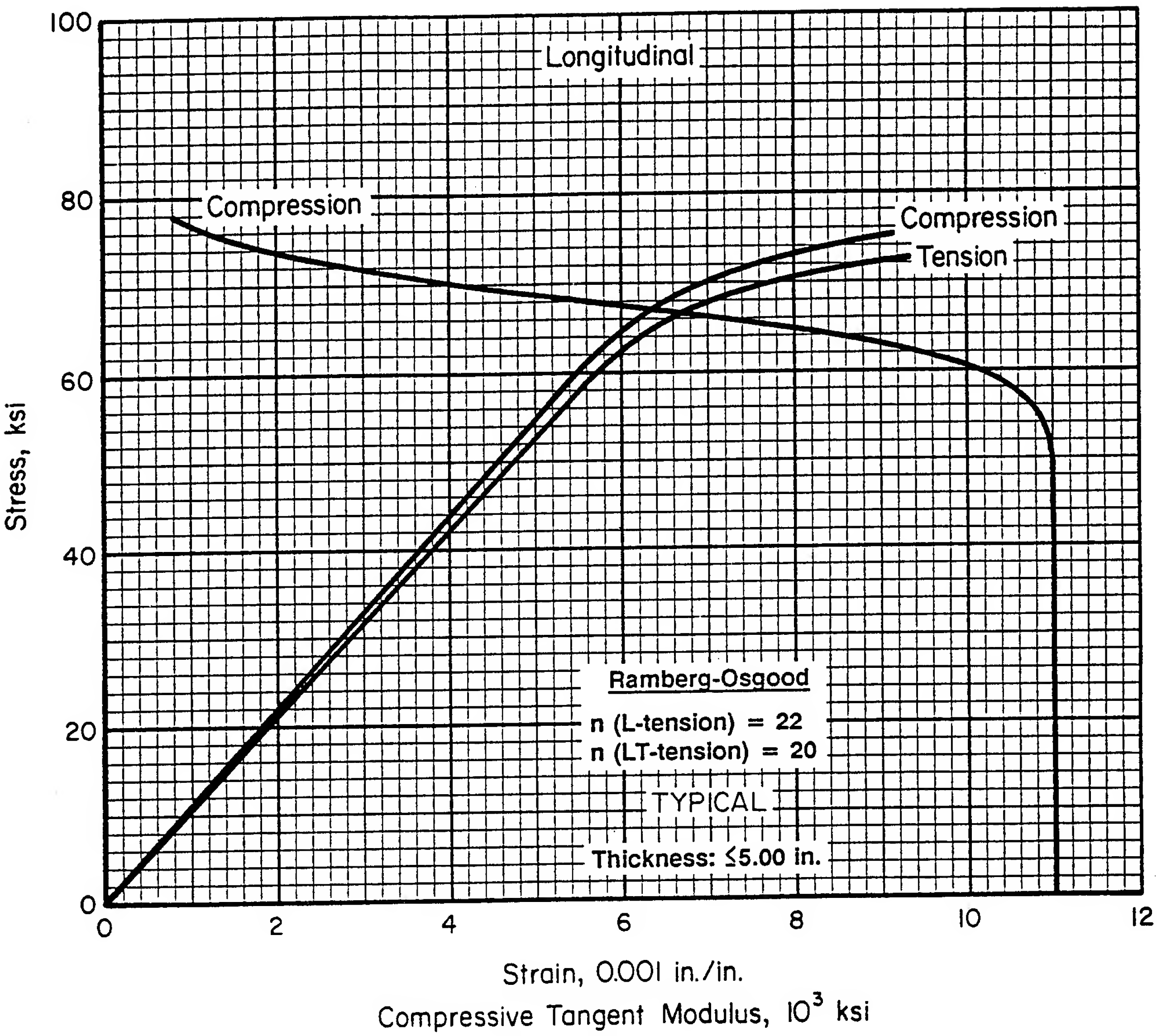


FIGURE 3.7.2.1.6(g). *Typical tensile and compressive stress-strain and compressive tangent-modulus curves for 7049/7149-T73511 extrusion at room temperature.*

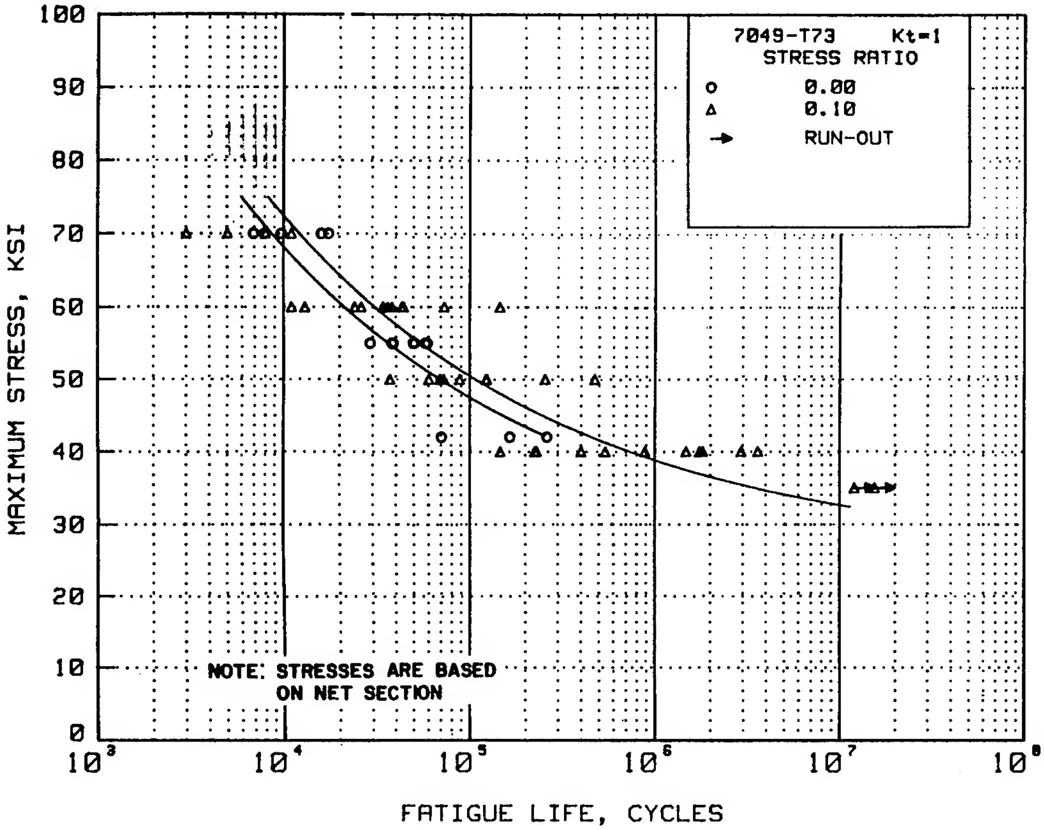


FIGURE 3.7.2.1.8(a). *Best-fit S/N curves for unnotched 7049-T73 die and hand forgings, at room temperature, longitudinal and long-transverse directions.*

Correlative Information for Figure 3.7.2.1.8(a)

Product Form: Die forging, 3 and 4.5 inches thick. Hand forging, 2, 3, 4, and 5 inches thick

Properties:	TUS, ksi	TYS, ksi	Temp., F
(L)	78	70	RT
(LT)	74	65	RT

Specimen Details: Unnotched
Uniform Gage, 0.200-inch net diameter (Ref. a)
Hourglass, 0.225 inch net diameter (Ref. b)
3.000-inch test section radius
Hourglass, 0.300-inch net diameter (Ref. d)
9.875-inch test section radius

Surface Condition:
Longitudinallypolished to 4 RMS finish or better (Ref. a)
Unspecified (Ref. b)

References: 3.7.2.1.8(a), (b), and 3.2.6.1.9(d)

Test Parameters:
Loading - Axial
Frequency - 1800 cpm
Temperature - RT
Environment - Lab air

No. of Heats/Lots: 6

Stress-Life Equation:
Log N_f = 9.95-3.62 log (S_{eq} - 24.2)
$S_{eq} = S_{max}(1\text{-}R)^{0.57}$
Standard Error of Estimate = 0.346
Standard Deviation in Life = 0.736
R^2 = 78%

Sample Size = 50

[Caution: The equivalent stress model may provide unrealistic life predictions for stress ratios beyond those represented above]

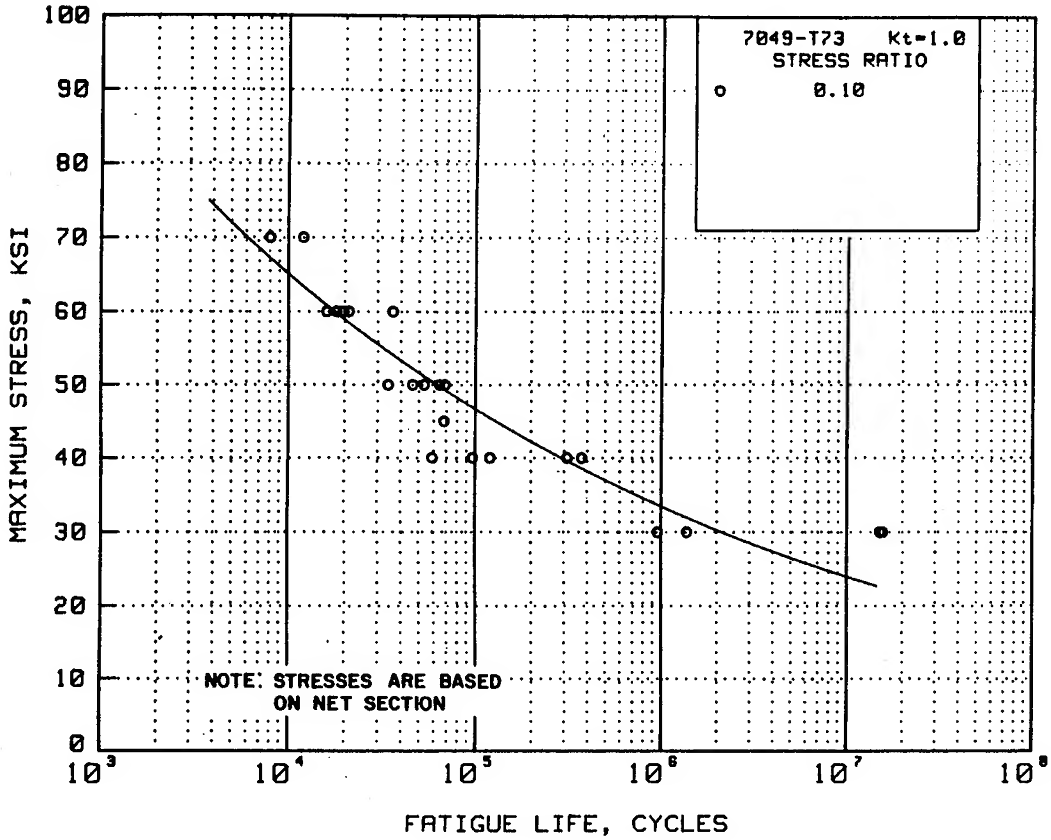


FIGURE 3.7.2.1.8(b). *Best-fit curves for unnotched 7049-T73 die forging, at room temperature, short transverse direction.*

Correlative Information for Figure 3.7.2.1.8(b)

Product Form: Die forging, 3 inches thick

Properties:	TUS, ksi	TYS, ksi	Temp., F
	73	64	RT

Specimen Details: Unnotched
0.200-inch net diameter

Surface Condition:
Longitudinally polished to 4μ in. finish with no circumferential marks

References: 3.7.2.1.8(a)

Test Parameters:
Loading - Axial
Frequency - 1800 cpm
Temperature - RT
Environment - Air

No. of Heats/Lots: 1

Equivalent Stress Equation:
Log N_f = 16.55-6.92 log (S_{max})
Standard Error of Estimate = 0.371
Standard Deviation in Life = 0.917
R^2 = 84%

Sample Size = 23

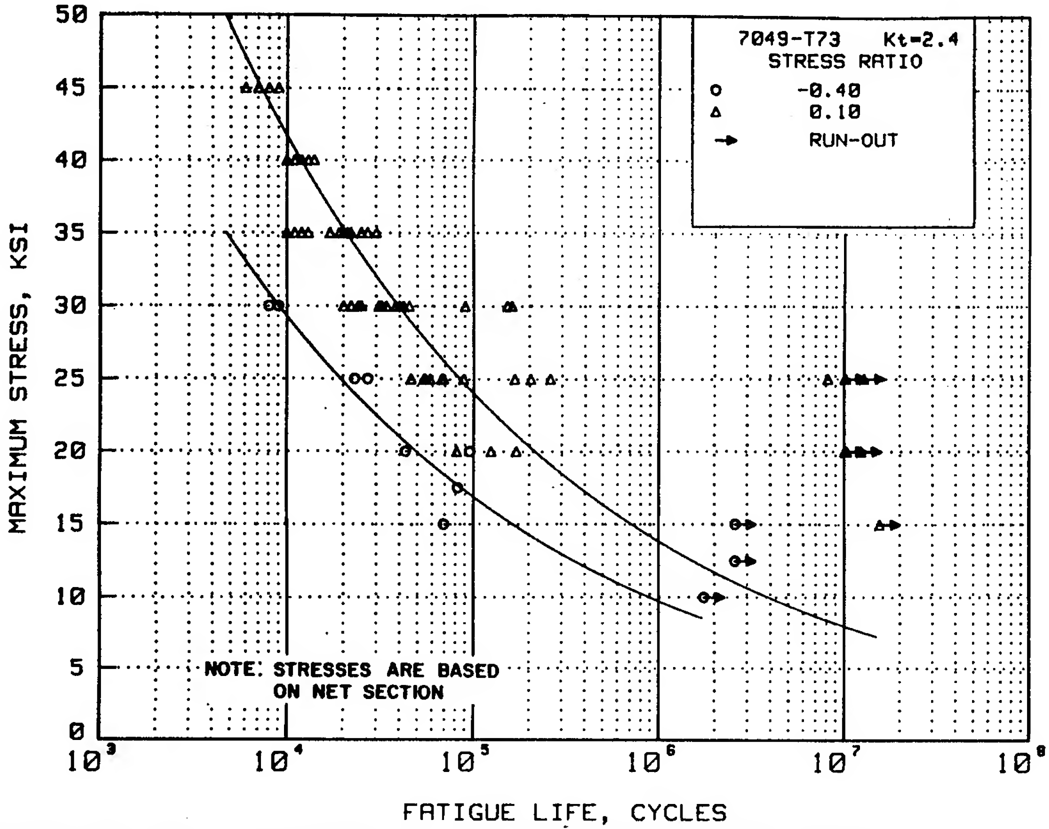


FIGURE 3.7.2.1.8(c). *Best-fit S/N curves for notched, K_t=2.4, 7049-T73 die forging, at room temperature, longitudinal, long-transverse, and short-transverse directions.*

Correlative Information for Figure 3.7.2.1.8(c)

Product Form: Die forging, 3 and 4.5 in. thick

Properties:	TUS, ksi	TYS, ksi	Temp., F
(L)	77	68	RT Unnotched
	95	--	RT Notched
(LT)	73	64	RT Unnotched
	77	--	RT Notched
(ST)	75	66	RT Unnotched
	87	--	RT Notched

Specimen Details:

(Ref a.)	Circumferentially notched, $K_t = 2.4$ (Ref. c)
0.150 or 0.200 inch net diameter	0.350-inch net diameter
	0.500-inch gross diameter
	0.032-inch notch root radius, r
	60° flank angle, ω

Surface Condition:
Machined notch

References: 3.7.2.1.8(a) and (c)

Test Parameters:
Loading - Axial
Frequency - 1800 cpm
Temperature - RT
Environment - Lab air

No. of Heats/Lots: 2

Stress-Life Equation:
$\text{Log } N_f = 10.6\text{-}4.18 \log (S_{eq})$
$S_{eq} = S_{max}(1\text{-}R)^{0.80}$
Standard Error of Estimate = 0.320
Standard Deviation in Life = 0.500
R^2 = 59%

Sample Size = 69

[Caution: The equivalent stress model may provide unrealistic life predictions for stress ratios beyond those represented above]

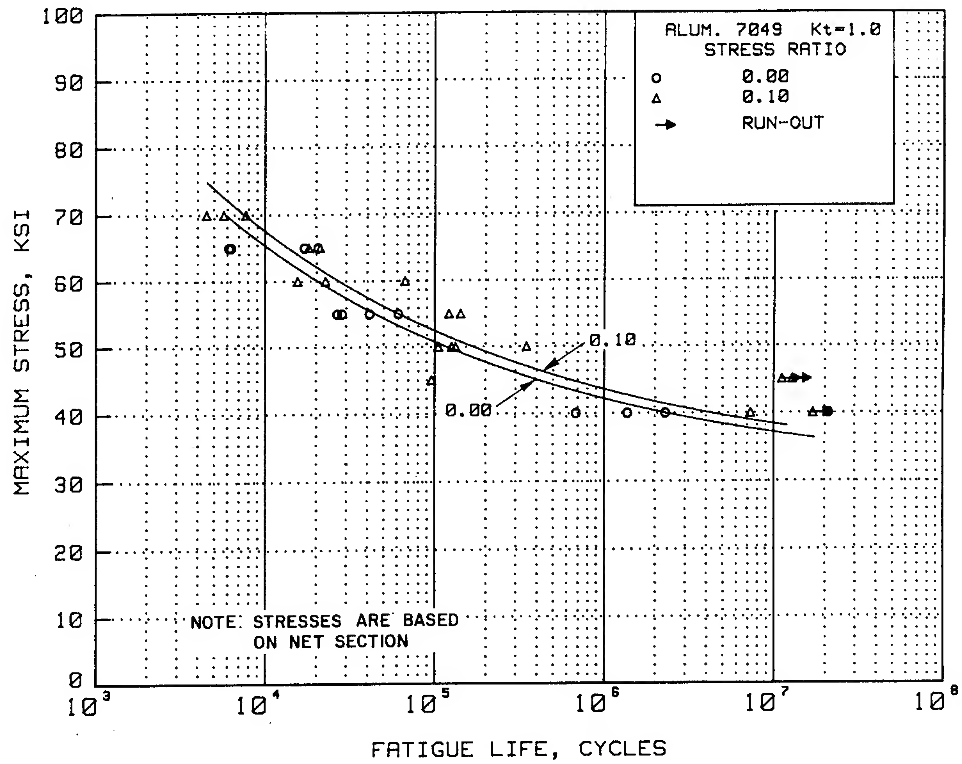


FIGURE 3.7.2.1.8(d) *Best-fit S/N curves for unnotched 7049-T73 hand forging, longitudinal direction.*

Correlative Information for Figure 3.7.2.1.8(d)

Product Form: Hand forging, 2.0- to 5.0-inches thick

Properties:	TUS, ksi	TYS, ksi	Temp.,F
	70-80	60-73	RT

Specimen Details: Unnotched
0.125- and 0.300-inch diameter

Surface Condition:
Polished with increasingly finer grits of emery paper to survace roughness of 10 rms with polishing marks longitudinal, or not specified.

References: 3.2.6.1.9(d) and 3.7.2.1.8(e)

Test Parameters:
Loading - Axial
Frequency - 800, 1500, or 1725 cpm
Temperature - RT
Environment - Air

No. of Heats/Lots: 6

Equivalent Stress Equation:
Log $N_f=10.6-4.31 \log (S_{eq}-30)$
$S_{eq}=S_{max}(1-R)^{0.31}$
Standard Error of Estimate=0.348
Standard Deviation in Life=0.944
$R^2=86\%$

Sample Size=28

(Caution: The equivalent stress model may provide unrealistic life predictions for stress ratios beyond those represented above.)

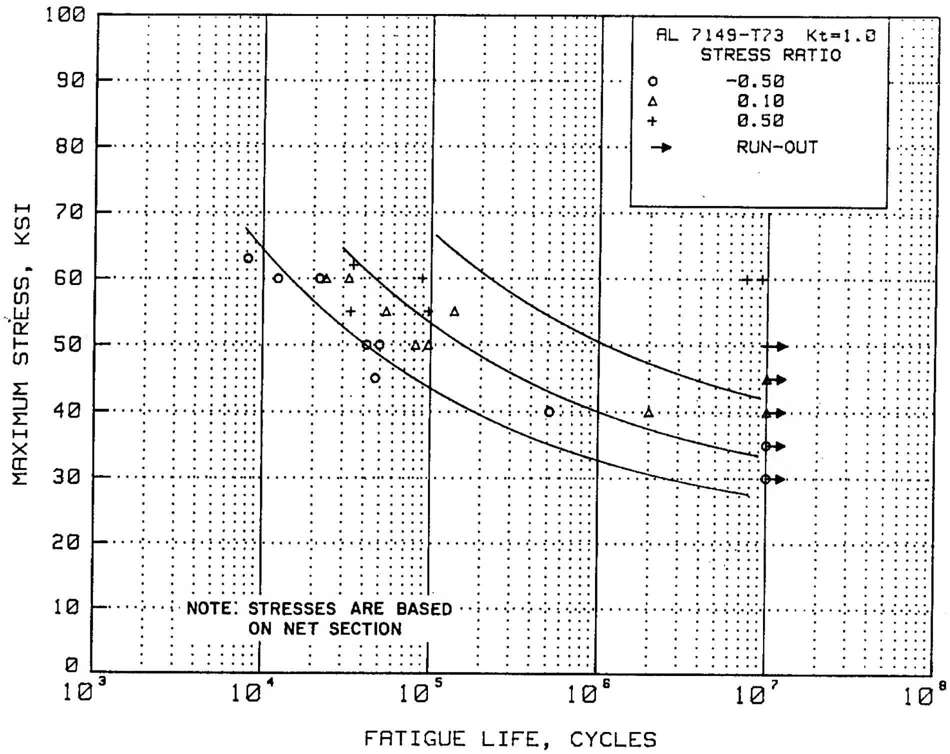


FIGURE 3.7.2.1.8(e). *Best-fit S/N curves for unnotched 7149-T73 hand forging, long transverse direction.*

Correlative Information for Figure 3.7.2.1.8(e)

Product Form: Hand forging, 4.00- to 4.75-inches thick

Properties:	TUS, ksi	TYS, ksi	Temp.,F
	73	64	RT

Specimen Details: Unnotched
0.250-inch diameter

Surface Condition: Not specified.

Reference: 3.7.2.1.8(e)

Test Parameters:
Loading - Axial
Frequency - Not specified
Temperature - RT
Environment - Air

No. of Heats/Lots: 3

Equivalent Stress Equation:
Log N_f=9.9-3.46 log (S_{eq}−25)
$S_{eq}=S_{max}(1-R)^{0.39}$
Standard Error of Estimate=0.689
Standard Deviation in Life=0.845
R^2=34%

Sample Size=20

(Caution: The equivalent stress model may provide unrealistic life predictions for stress ratios beyond those represented above.)

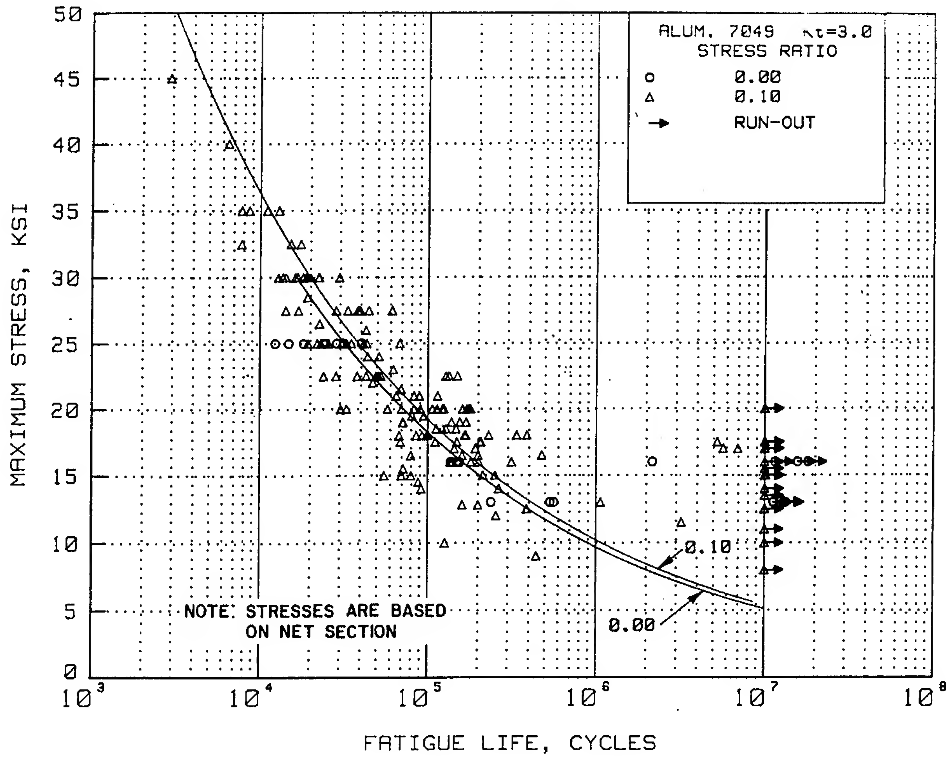


FIGURE 3.7.2.1.8(f). *Best-fit S/N curves for notched, K_t=3.0, 7049-T73 hand forging, longitudinal, long transverse, and short transverse directions.*

Correlative Information for Figure 3.7.2.1.8(f)

Product Form: Hand forging, 2.0- to 5.0-inches thick

Properties:	TUS, ksi	TYS, ksi	Temp.,F
	71-80	62-73	RT

Specimen Details: Circumferentially notched, K_t=3.0
0.200-, 0.300-, and 0.306-inch gross diameter
0.175-, 0.200-, and 0.253-inch net diameter
0.006, 0.010, and 0.013-inch root radius, r
60° flank angle, ω

Surface Condition:
Polished with oil and alumdum grit applied to a rotating wire, or not specified.

References: 3.2.6.1.9(d), 3.7.2.1.8(d) and (e)

Test Parameters:
Loading - Axial
Frequency - 800, 1500, or 1725 cpm
Temperature - RT
Environment - Air

No. of Heats/Lots: 8

Equivalent Stress Equation:
Log N_f=9.57-3.63 log (S_{eq})
$S_{eq}=S_{max}(1-R)^{0.49}$
Standard Error of Estimate=0.344
Standard Deviation in Life=0.562
R^2=63%

Sample Size=151

(Caution: The equivalent stress model may provide unrealistic life predictions for stress ratios beyond those represented above.)

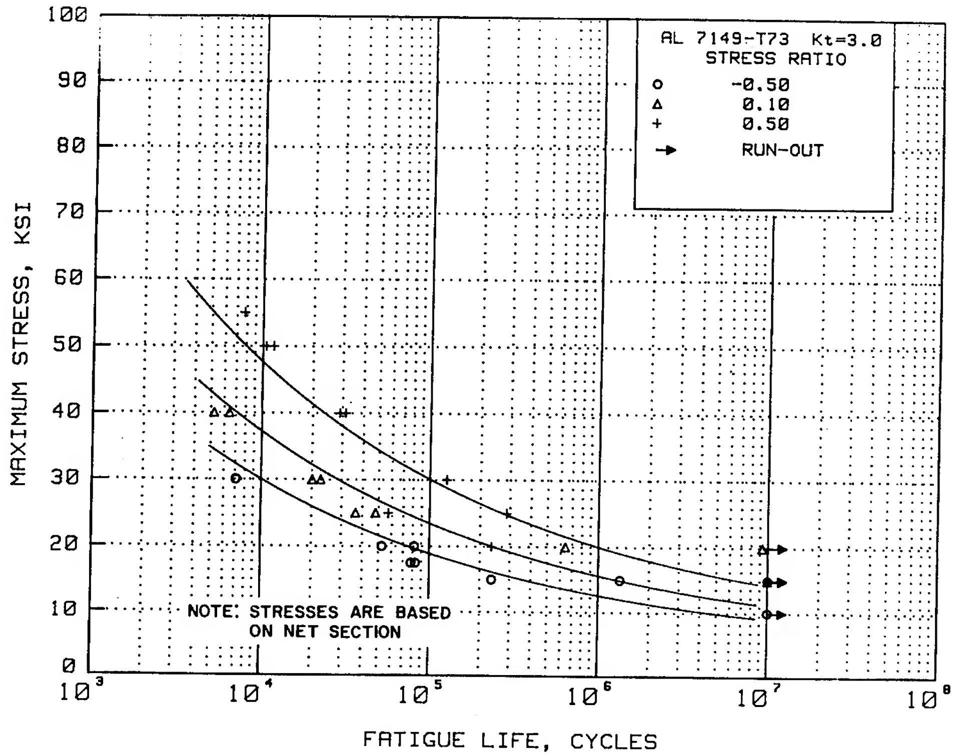


FIGURE 3.7.2.1.8(g). *Best-fit S/N curves for notched, K_t = 3.0, 7149-T73 hand forging, long transverse direction.*

Correlative Information for Figure 3.7.2.1.8(g)

Product Form: Hand forging, 4.00- to 4.75-inches thick

Properties:	TUS, ksi	TYS, ksi	Temp.,F
	73	64	RT

Specimen Details: Circumferentially notched, K_t=3.0
0.375-inch gross diameter
0.253-inch net diameter
0.013-inch root radius, r
60° flank angle, ω

Surface Condition: Not specified

Reference: 3.7.2.1.8(e)

Test Parameters:
Loading - Axial
Frequency - Not specified
Temperature - RT
Environment - Air

No. of Heats/Lots: 3

Equivalent Stress Equation:
$\log N_f = 10.1 - 4.10 \log (S_{eq} - 5)$
$S_{eq} = S_{max}(1-R)^{0.42}$
Standard Error of Estimate=0.450
Standard Deviation in Life=0.797
R^2=68%

Sample Size=25

(Caution: The equivalent stress model may provide unrealistic life predictions for stress ratios beyond those represented above.)

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3.7.3 7050 ALLOY

3.7.3.0 *Comments and Properties.*—7050 is an Al-Zn-Mg-Cu-Zr alloy developed to have a combination of high strength, high resistance to stress-corrosion cracking, and good fracture toughness, particularly in thick sections. The use of zirconium in lieu of chromium provides a low sensitivity to quench, which results in high strengths in thick sections. Plate, hand, and die forgings in the T74-type temper have static strengths about equivalent to those of corresponding products of 7079 in the T6-type tempers and toughness levels equal to or higher than other conventional high-strength alloys.

Plate in the T7451 temper has stress-corrosion resistance higher than 7075-T7651, and hand and die forgings in the T7452 and T74 tempers, respectively, have stress-corrosion resistance similar to 7175-T74 forgings. The T73-type temper provides the highest resistance to stress corrosion for this alloy. The T76-type temper provides for good exfoliation resistance and higher stress-corrosion resistance than T6-type tempers of 7075 and 7178. The T74-type temper provides stress-corrosion and strength characteristics intermediate to those of T76 and T73. Refer to Section 3.1.2.3 for further comments regarding the resistance of the alloy to stress-corrosion cracking.

Refer to Section 3.1.3.4 for comments regarding the weldability of the alloy.

Material specifications for 7050 are shown in Table 3.7.3.0(a). Room-temperature properties are shown in Table 3.7.3.0(b_1) through (e_3).

TABLE 3.7.3.0(a). *Material Specifications for 7050 Aluminum Alloy*

Specification	Form
AMS 4050	Bare plate
AMS 4108	Hand forging
AMS 4107	Die forging
AMS 4333	Die forging
AMS 4340	Extruded shape
AMS 4341	Extruded shape
AMS 4342	Extruded shape
AMS 4201	Bare plate
MIL-A-22771	Forging

The temper index for 7050 is as follows:

Section	Temper
3.7.3.1	T73510 and T73511
	T74, T7451, and T7452 (formerly T736, T73651, T73652)
3.7.3.3	T76510 and T76511

3.7.3.1 *T73510 and T73511 Tempers.*—Figures 3.7.3.1.6(a) through (d) present stress-strain and tangent-modulus curves for extrusions. Fatigue data are presented in Figures 3.7.3.1.8(a) and (b).

3.7.3.2 *T74, T7451, and T7452 Tempers.*—Elevated temperature curves for T7451 plate are presented in Figure 3.7.3.2.1. Figures 3.7.3.2.6(a) through (j) present stress-strain and tangent-modulus curves for various products and tempers. Fatigue data are presented in figures 3.7.3.2.8(a) through (i). Fatigue-crack-propagation data for T7451 plate are presented in Figures 3.7.3.2.9(a) through (c).

3.7.3.3 *T76510 and T76511 Tempers.*—Figures 3.7.3.3.6(a) through (f) present stress-strain and tangent-modulus curves for extruded shapes. Fatigue data are presented in Figure 3.7.3.3.8(a) and (b).

TABLE 3.7.2.0(b$_1$). *Design Mechanical and Physical Properties of 7050 Aluminum Alloy Plate*

Specification	AMS 4050											
Form	Plate											
Temper	T7451											
Thickness, in.	0.250-1.500		1.501-2.000		2.001-3.000		3.001-4.000		4.001-5.000		5.001-6.000	
Basis	A	B	A	B	A	B	A	B	A	B	A	B
Mechanical Properties:												
F_{tu}, ksi:												
L	74[b]	76	74	76	73[b]	75	72	74	71[b]	73	70[b]	72
LT	74	76	74[b]	76	73[b]	75	72	75	71[b]	74	70	73
ST	...	...	...	...	68	72	68[b]	71	67	70	66	69
F_{ty}, ksi:												
L	64[b]	67	64[b]	66	63[b]	66	62[b]	65	61[b]	65	60	63
LT	64	66	64	66	63[b]	66	62	65	61	64	60	62
ST	...	...	...	...	59	61	57	60	57[b]	60	57	59
F_{cy}, ksi:												
L	63	64	62	64	61	64	60	63	58	61	57	59
LT	66	68	67	69	66	69	65	68	64	67	63	66
ST	...	...	...	...	63	66	63	66	63	66	62	64
F_{su}, ksi	42	43	43	44	43	44	43	45	43	45	43	45
F_{bru}[a], ksi:												
(e/D = 1.5)	107	110	109	112	108	111	107	111	107	111	105	110
(e/D = 2.0)	140	144	142	146	141	144	140	144	138	144	137	142
F_{bry}[a], ksi:												
(e/D = 1.5)	86	89	89	92	89	93	90	94	90	95	91	94
(e/D = 2.0)	101	104	104	107	104	109	104	109	105	110	105	108
e, percent (S-basis):												
L	10	...	10	...	9	...	9	...	9	...	8	...
LT	9	...	9	...	6	...	6	...	5	...	4	...
ST	...	...	...	...	2	...	2	...	2	...	2	...
E, 10^3 ksi	10.3											
E_c, 10^3 ksi	10.6											
G, 10^3 ksi	3.9											
μ	0.33											
Physical Properties:												
ω, lb/in.^{3}	0.102											
C, Btu/(lb)(F)	0.23 (at 212 F)											
K, Btu/[(hr)(ft^2)(F)/ft]	91 (at 77 F)											
α, 10^{-6} in./in./F ...	12.8 (68 to 212 F)											

[a]See Table 3.1.2.1.1. Bearing values are "dry pin" values per Section 1.4.7.1.
[b]S-basis. See Table 3.7.3.0(b$_2$) for A values which exceed S values.

TABLE 3.7.3.0(b$_2$). *A Values for Tensile Yield and Ultimate Strength for 7050-T7451 Plate*

Thickness, in.	0.250-1.500	1.501-2.000	2.001-3.000	3.001-4.000	4.001-5.000	5.001-6.000
Mechanical Properties:						
F_{tu}, ksi:						
L	75	...	74	...	72	71
LT	...	75	74	...	72	...
ST	...	...	...	69	...	...
F_{ty}, ksi:						
L	65	65	65	63	62	...
LT	...	...	64	...	...	...
ST	...	...	...	...	58	...

TABLE 3.7.3.0(b$_3$). *Design Mechanical and Physical Properties of 7050 Aluminum Alloy Plate*

Specification	AMS 4201							
Form	Plate							
Temper	T7651							
Thickness, in.	0.250-1.000	1.001-1.500		1.501-2.000		2.001-2.500		2.501-3.000
Basis	S	A	B	A	B	A	B	S
Mechanical Properties:								
F_{tu}, ksi:								
L	76	77[b]	80	76	78	75	78	76
LT	76	76	79	75	78	75	78	76
ST	...	...	...	72	75	70	73	70
F_{ty}, ksi:								
L	66	67[b]	71	66	70	66	70	66
LT	66	66	70	65	69	65	69	66
ST	...	...	...	59	63	60	62	60
F_{cy}, ksi:								
L	64	64	68	64	67	64	67	64
LT	68	68	73	68	72	68	72	69
ST	...	...	...	67	71	67	71	68
F_{su}, ksi	43	44	46	44	46	45	47	46
F_{bru}[a], ksi:								
(e/D = 1.5)	110	112	117	112	117	114	118	116
(e/D = 2.0)	142	144	150	144	150	146	151	149
F_{bry}[a], ksi:								
(e/D = 1.5)	87	90	96	91	96	93	98	96
(e/D = 2.0)	102	105	111	105	112	107	114	110
e, percent (S-basis):								
L	9	9	...	9	...	8	...	8
LT	8	8	...	8	...	7	...	7
ST	...	...	...	...	...	1.5	...	1.5
E, 10^3 ksi	10.3							
E_c, 10^3 ksi	10.8							
G, 10^3 ksi	4.0							
μ	0.33							
Physical Properties:								
ω, lb/in.^{3}	0.102							
C, Btu/(lb)(F)	0.23 (at 212 F)							
K, Btu/[(hr)(ft^2)(F)/ft]	89 (at 77 F)							
α, 10^{-6} in./in./F	12.8 (68 to 212 F)							

[a]See Table 3.1.2.1.1. Bearing values are "dry pin" values per Section 1.4.7.1.
[b]S-basis values since A values could not be determined.

TABLE 3.7.3.0(c_1). *Design Mechanical and Physical Properties of 7050 Aluminum Alloy Die Forging*

Specification	AMS 4107 and MIL-A-22771			
Form	Die forging			
Temper	T74[a]			
Thickness[b], in.	≤2.000	2.001-4.000	4.001-5.000	5.001-6.000
Basis	S	S	S	S
Mechanical Properties:				
F_{tu}, ksi:				
L	72	71	70	70
T[c]	68	67	66	66
F_{ty}, ksi:				
L	62	61	60	59
T[c]	56	55	54	54
F_{cy}, ksi:				
L	63	63	63	62
ST	60	59	58	57
F_{su}, ksi	42	42	41	41
F_{bru}[d], ksi:				
(e/D = 1.5)	99	98	97	97
(e/D = 2.0)	131	129	127	127
F_{bry}[d], ksi:				
(e/D = 1.5)	82	81	78	78
(e/D = 2.0)	96	95	92	92
e, percent:				
L	7	7	7	7
T[c]	5	4	3	3
E, 10^3 ksi	10.2			
E_c, 10^3 ksi	10.7			
G, 10^3 ksi	3.9			
μ	0.33			
Physical Properties:				
ω, lb/in.^{3}	0.102			
C, Btu/(lb)(F)	0.23 (at 212 F)			
K, Btu/[(hr)(ft^2)(F)/ft]	91 (at 77 F)			
α, 10^{-6} in./in./F	12.8 (68 to 212 F)			

[a]Design values were based upon data obtained from testing T74 die forgings, heat treated by suppliers and supplied in T74 temper.
[b]Thickness at the time of heat treatment. When die forgings are machined before heat treatment, the mechanical properties are applicable provided the as-forged thickness is not greater than twice the thickness at the time of heat treatment.
[c]For die forgings, T indicates any grain direction not within ±15° of being parallel to the forging flow lines with the axis of the specimen located as close to the short transverse direction as possible. F_{cy}(T) values are based upon short transverse test data.
[d]Bearing values are "dry pin" values per Section 1.4.7.1.

TABLE 3.7.3.0(c_2). *Design Mechanical and Physical Properties of 7050 Aluminum Alloy Die Forging—Continued*

Specification	AMS 4333	
Form	Die forging	
Temper	T7452	
Thickness[a], in.	≤ 2.000	2.001-4.000
Basis	S	S
Mechanical Properties:		
F_{tu}, ksi:		
L	72	71
T[a]	68	67
F_{ty}, ksi:		
L	60	59
T[a]	55	53
F_{cy}, ksi:		
L	63	62
ST	63	62
F_{su}, ksi	43	43
F_{bru}[b], ksi:		
(e/D = 1.5)	102	101
(e/D = 2.0)	136	135
F_{bry}[b], ksi:		
(e/D = 1.5)	87	85
(e/D = 2.0)	104	102
e, percent:		
L	9	8
T[a]	5	4
E, 10^3 ksi	10.2	
E_c, 10^3 ksi	10.5	
G, 10^3 ksi	3.9	
μ	0.33	
Physical Properties:		
ω, lb/in.^{3}	0.102	
C, Btu/(lb)(F)	0.23 (at 212 F)	
K, Btu/[(hr)(ft^2)(F)/ft]	91 (at 77 F)	
α, 10^{-6} in./in./F	12.8 (68 to 212 F)	

[a]For die forgings, T indicates any grain direction not with ± 15° of being parallel to the forging flow lines with the axis of the specimen located as close to the short transverse direction as possible.
[b]Bearing values are "dry pin" values per Section 1.4.7.1.

TABLE 3.7.3.0(d). *Design Mechanical and Physical Properties of 7050 Aluminum Alloy Hand Forging*

Specification	AMS 4108 and MIL-A-22771							
Form	Hand Forging							
Temper	T7452							
Thickness, in.	≤2.000	2.001-3.000	3.001-4.000	4.001-5.000	5.001-6.000	6.001-7.000		7.001-8.000
Basis	S	S	S	S	S	A	B	S
Mechanical Properties:								
F_{tu}, ksi:								
L	72	72	71	70	69	68	71	67
LT	71	70	70	69	68	67	70	66
ST	...	67	67	66	66	65	69	64
F_{ty}, ksi:								
L	63	62	61	60	59	56	61	57
LT	61	60	59	58	56	54[b]	59	52
ST	...	55	55	54	53	51[b]	56	50
F_{cy}, ksi:								
L	63	62	61	60	58	56	61	54
LT	64	63	62	61	59	57	62	55
ST	...	63	61	60	58	56	61	54
F_{su}, ksi	42	41	41	41	40	40	41	39
F_{bru}[a], ksi:								
(e/D = 1.5)	98	97	97	96	94	93	97	91
(e/D = 2.0)	131	129	129	127	125	123	129	121
F_{bry}[a], ksi:								
(e/D = 1.5)	86	84	83	82	79	76	83	73
(e/D = 2.0)	101	100	98	96	93	90	98	86
e, percent (S-basis):								
L	9	9	9	9	9	9	...	9
LT	5	5	5	4	4	4	...	4
ST	...	4	4	3	3	3	...	3
E, 10^3 ksi	10.2							
E_c, 10^3 ksi	10.6							
G, 10^3 ksi	3.9							
μ	0.33							
Physical Properties:								
ω, lb/in.^{3}	0.102							
C, Btu/(lb)(F)	0.23 (at 212 F)							
K, Btu/[(hr)(ft^2)(F)/ft]	91 (at 77 F)							
α, 10^{-6} in./in./F	12.8 (68 to 212 F)							

[a]Bearing values are "dry pin" values per Section 1.4.7.1.
[b]S-basis. The A values for F_{ty}(LT) = 56 ksi and F_{ty}(ST) = 52 ksi.

TABLE 3.7.3.0(e_1). *Design Mechanical and Physical Properties of 7050 Aluminum Alloy Extrusion*

Specification	AMS 4341				
Form	Extrusion				
Temper	T73511				
Cross-sectional area, in^2	≤32				
Thickness or diameter, in.	≤1.000	1.001-2.000	2.001-3.000	3.001-4.000	4.001-5.000
Basis	S	S	S	S	S
Mechanical Properties:					
F_{tu}, ksi:					
L	70	70	70	70	70
LT	68	66	65	63	62
F_{ty}, ksi:					
L	60	60	60	60	60
LT	57	56	55	53	52
F_{cy}, ksi:					
L	60	60	60	61	61
LT	60	59	58	56	56
F_{su}, ksi	39	39	38	37	36
F_{bru}[a], ksi:					
(e/D = 1.5)	103	100	96	91	87
(e/D = 2.0)	133	129	124	120	115
F_{bry}[a], ksi:					
(e/D = 1.5)	82	80	78	76	74
(e/D = 2.0)	97	95	93	91	88
e, percent:					
L	8	8	8	8	8
E, 10^3 ksi	10.3				
E_c, 10^3 ksi	10.7				
G, 10^3 ksi	3.9				
μ	0.33				
Physical Properties:					
ω, lb/in.^{3}	0.102				
C, Btu/(lb)(F)	0.23 (at 212 F)				
K, Btu/[(hr)(ft^2)(F)/ft]	93 (at 77 F)				
α, 10^{-6} in./in./F	12.8 (68 to 212 F)				

[a]Bearing values are "dry pin" values per Section 1.4.7.1.

TABLE 3.7.3.0(e_2). *Design Mechanical and Physical Properties of 7050 Aluminum Alloy Extrusion*

Specification	AMS 4342				
Form	Extrusion[b]				
Temper	T73511				
Cross-sectional area, in^2	≤32				
Thickness or diameter, in.	≤1.000	1.001-2.000	2.001-3.000	3.001-4.000	4.001-5.000
Basis	S	S	S	S	S
Mechanical Properties:					
F_{tu}, ksi:					
L	73	73	73	73	73
LT	71	69	68	64	64
F_{ty}, ksi:					
L	63	63	63	63	63
LT	60	59	58	56	54
F_{cy}, ksi:					
L	63	63	63	64	64
LT	63	62	61	59	57
F_{su}, ksi	41	40	40	39	38
F_{bru}[a], ksi:					
(e/D = 1.5)	107	104	100	95	91
(e/D = 2.0)	139	135	130	125	121
F_{bry}[a], ksi:					
(e/D = 1.5)	86	84	82	80	78
(e/D = 2.0)	106	100	98	95	92
e, percent:					
L	7	7	7	7	7
E, 10^3 ksi	10.3				
E_c, 10^3 ksi	10.7				
G, 10^3 ksi	3.9				
μ	0.33				
Physical Properties:					
ω, lb/in.^{3}	0.102				
C, Btu/(lb)(F)	0.23 (at 212 F)				
K, Btu/[(hr)(ft^2)(F)/ft]	93 (at 77 F)				
α, 10^{-6} in./in./F	12.8 (68 to 212 F)				

[a]Bearing values are "dry pin" values per Section 1.4.7.1.
[b] Excluding tubing.

TABLE 3.7.3.0(e_3). *Design Mechanical and Physical Properties of 7050 Aluminum Alloy Extrusion*

Specification	AMS 4340						
Form	Extrusion						
Temper	T76511						
Thickness, in.	≤0.499		0.500-1.000	1.001-2.000	2.001-3.000	3.001-4.000	4.001-5.000
Basis	A	B	S	S	S	S	S
Mechanical Properties:							
F_{tu}, ksi:							
L	77	79	79	79	79	79	79
LT	76	78	77	75	73	71	68
F_{ty}, ksi:							
L	68	71	69	69	69	69	69
LT	67	69	67	65	63	61	59
F_{cy}, ksi:							
L	68	71	69	69	69	69	69
LT	70	73	70	69	67	66	64
F_{su}, ksi	42	44	43	43	42	41	40
$F_{bru}{}^{a}$, ksi:							
(e/D = 1.5)	113	116	115	114	110	107	103
(e/D = 2.0)	147	151	150	148	144	140	136
$F_{bry}{}^{a}$, ksi:							
(e/D = 1.5)	94	98	94	92	89	86	82
(e/D = 2.0)	109	114	110	108	104	98	93
e, percent (S-basis):							
L	7	...	7	7	7	7	7
E, 10^3 ksi	10.3						
E_c, 10^3 ksi	10.7						
G, 10^3 ksi	3.9						
μ	0.33						
Physical Properties:							
ω, lb/in.^{3}	0.102						
C, Btu/(lb)(F)	0.23 (at 212 F)						
K, Btu/[(hr)(ft^2)(F)/ft]	89 (at 77 F)						
α, 10^{-6} in./in./F	12.8 (68 to 212 F)						

[a]Bearing values are "dry pin" values per Section 1.4.7.1.

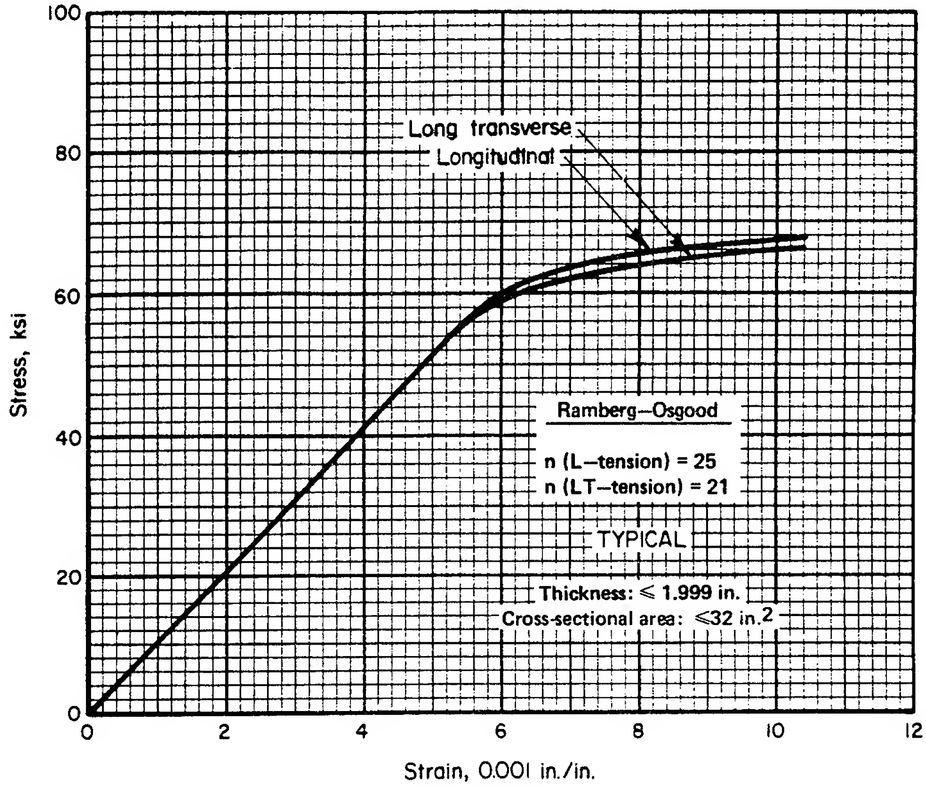

FIGURE 3.7.3.1.6(a). *Typcal tensile stress-strain curve for 7050-T7351X aluminum alloy extrusion at room temperature.*

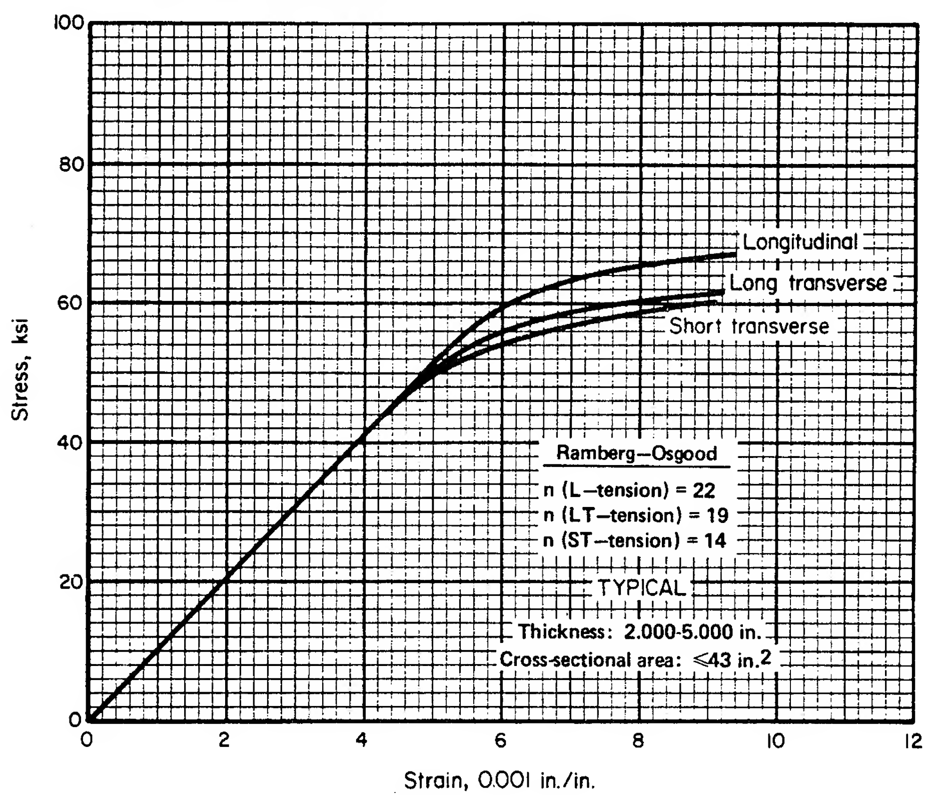

FIGURE 3.7.3.1.6(b). *Typical tensile stress-strain curve for 7050-T7351X aluminum alloy extrusion at room temperature.*

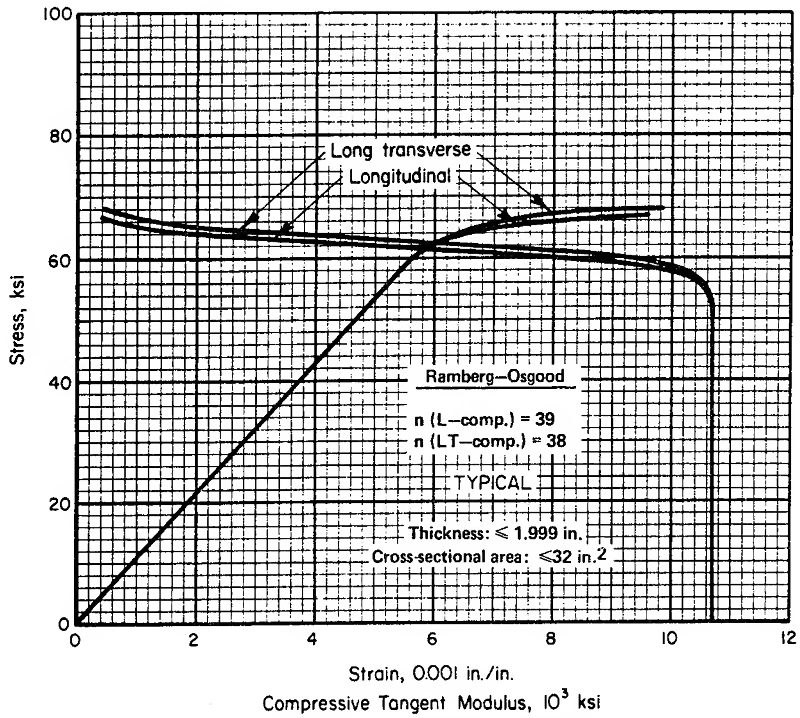

FIGURE 3.7.3.1.6(c). *Typical compressive stress-strain and tangent-modulus curves for 7050-T7351X aluminum alloy extrusion at room temperature.*

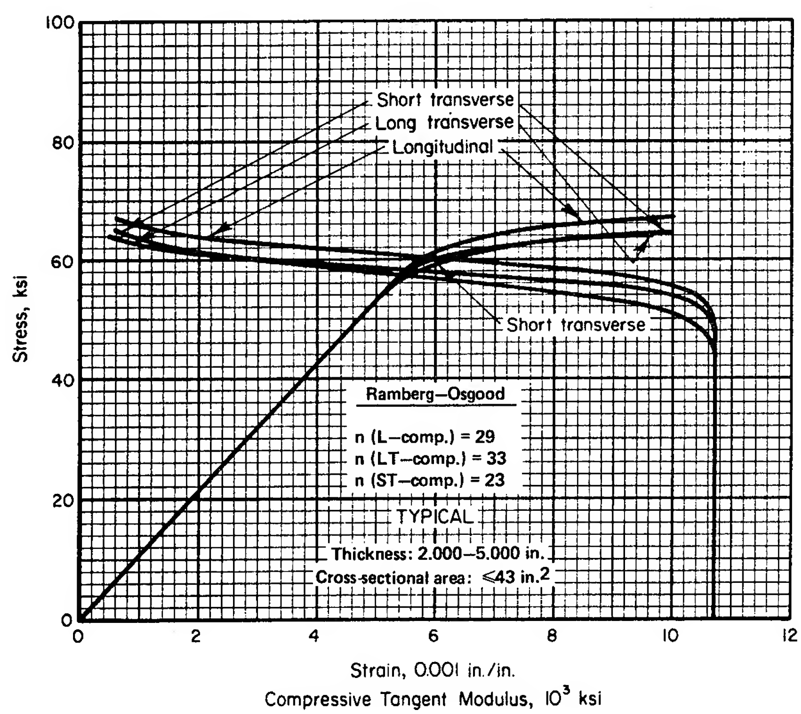

FIGURE 3.7.3.1.6(d). *Typical compressive stress-strain and tangent-modulus curves for 7050-T7351X aluminum alloy extrusion at room temperature.*

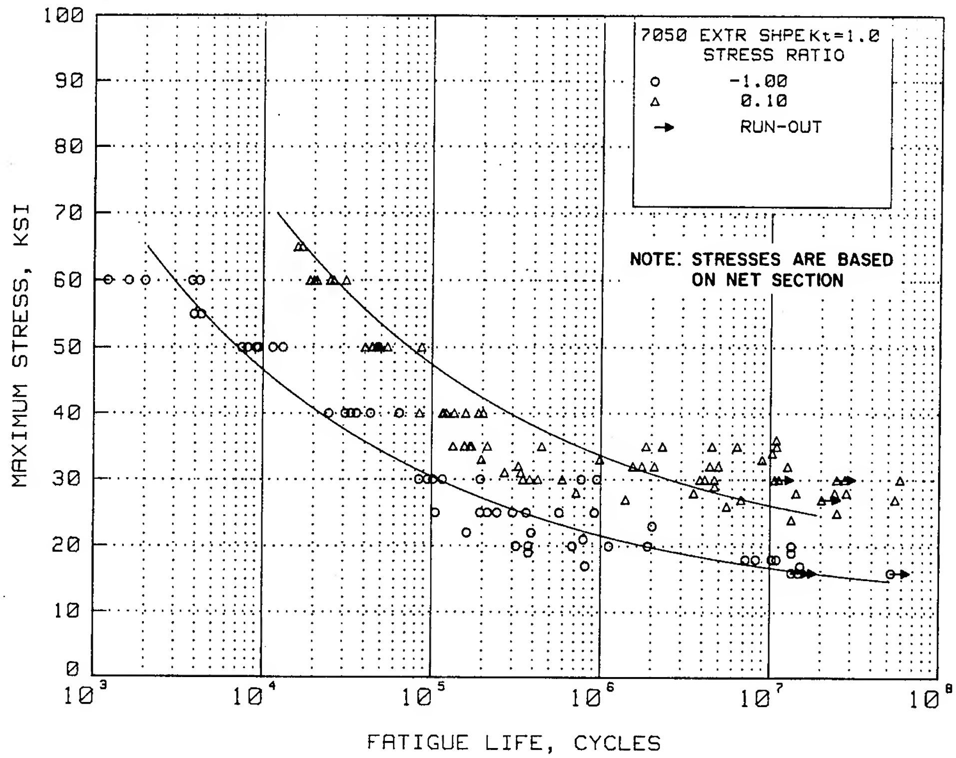

FIGURE 3.7.3.1.8(a). *Best-fit S/N curve for unnotched 7050-T7351X extruded shape, longitudinal and long transverse directions.*

Correlative Information for Figure 3.7.3.1.8(a)

Product Form: Extruded shape, 0.5-5.0-inch thick

Properties:	TUS, ksi	TYS, ksi	Temp.,F
	72-79	62-69	RT

Specimen Details: Unnotched
0.300-inch diameter

Surface Condition: Not specified

References: 3.7.3.2.9(b) and 3.7.7.2.8(b)

Test Parameters:
Loading - Axial
Frequency - 800 cpm
Temperature - RT
Environment - Air

No. of Heats/Lots: Not specified

Equivalent Stress Equation:
Log N_f=10.5-3.79 log ($S_{eq}-16$)
$S_{eq}=S_{max}(1-R)^{0.55}$
Standard Error of Estimate=0.516
Standard Deviation in Life=1.10
R^2=78%

Sample Size=128

(Caution: The equivalent stress model may provide unrealistic life predictions for stress ratios beyond those represented above.)

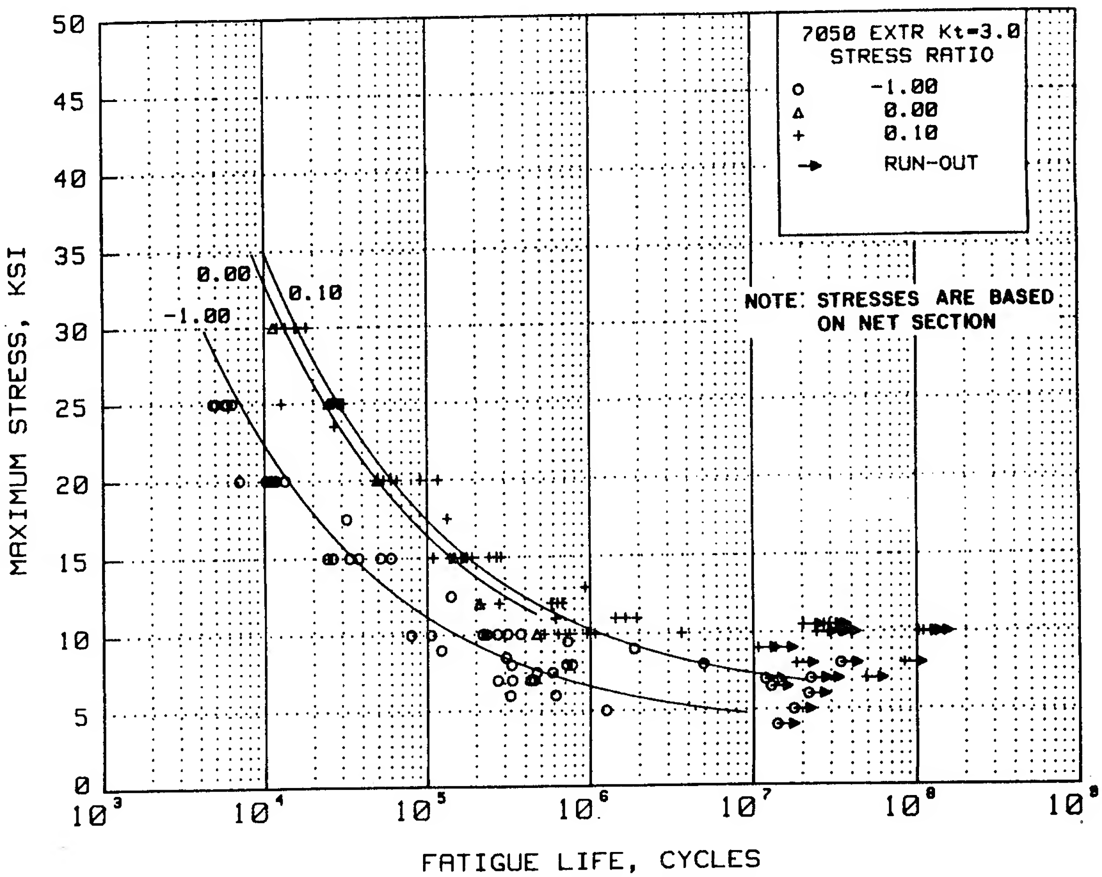

FIGURE 3.7.3.1.8(b). *Best-fit S/N curve for notched, $K_t=3.0$, 7050-T7351X extruded shape, longitudinal and long transverse directions.*

Correlative Information for Figure 3.7.3.1.8(b)

Product Form: Extruded shape, 0.5-5.0 inch thick

Properties:

TUS, ksi	TYS, ksi	Temp., F
72-79	62-69	RT

Specimen Details: Circumferentially notched, $K_t=3.0$
0.359-inch gross diameter
0.253-inch net diameter
0.013-inch root radius, r
60° flank angle, ω

Surface Condition: Not specified

Reference: 3.7.3.2.9(b) and 3.7.7.2.8(b)

Test Parameters:
Loading - Axial
Frequency - 800 cpm
Temperture - RT
Environment - Air

No. of Heats/Lots: Not specified

Equivalent Stress Equation:
Log N_f = 7.73-2.58 log (S_{eq} - 5.0)
$S_{eq} = S_{max} (1\text{-}R)^{0.56}$
Standard Error of Estimate = 0.268
Standard Deviation in Life = 0.733
R^2 = 87%

Sample Size = 103

[Caution: The equivalent stress model may provide unrealistic life predictions for stress ratios beyond those represented above.]

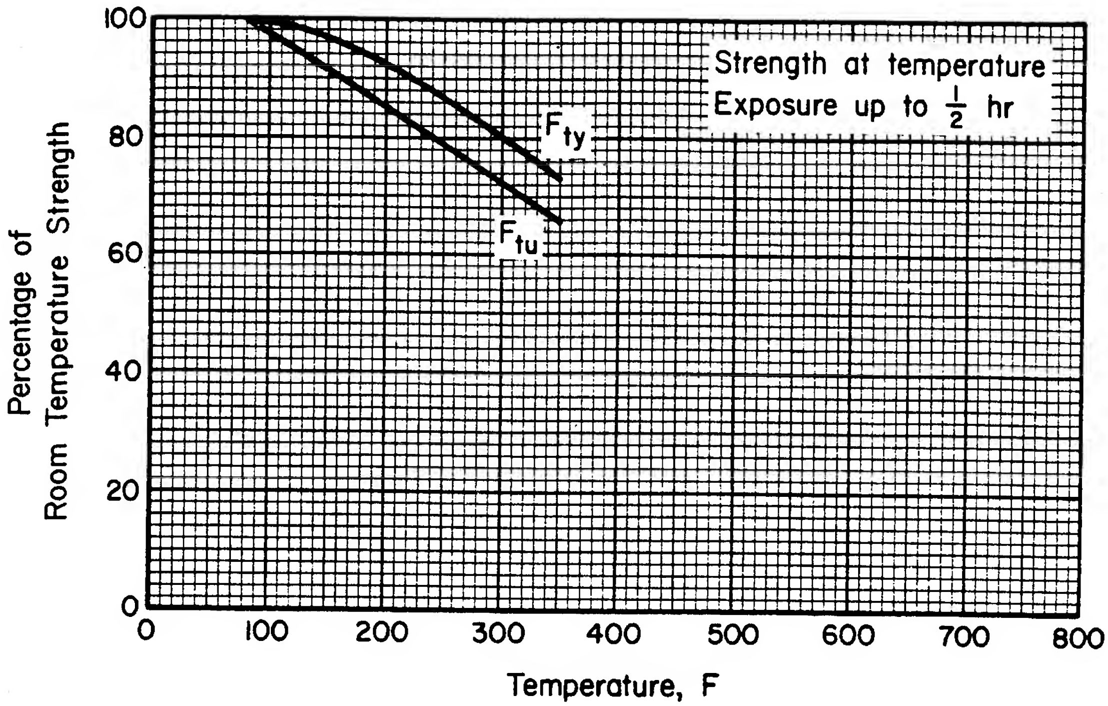

FIGURE 3.7.3.2.1. *Effect of temperature on the tensile ultimate strength (F_{tu}) and the tensile yield strength (F_{ty}) of 7050-T7451 aluminum alloy plate.*

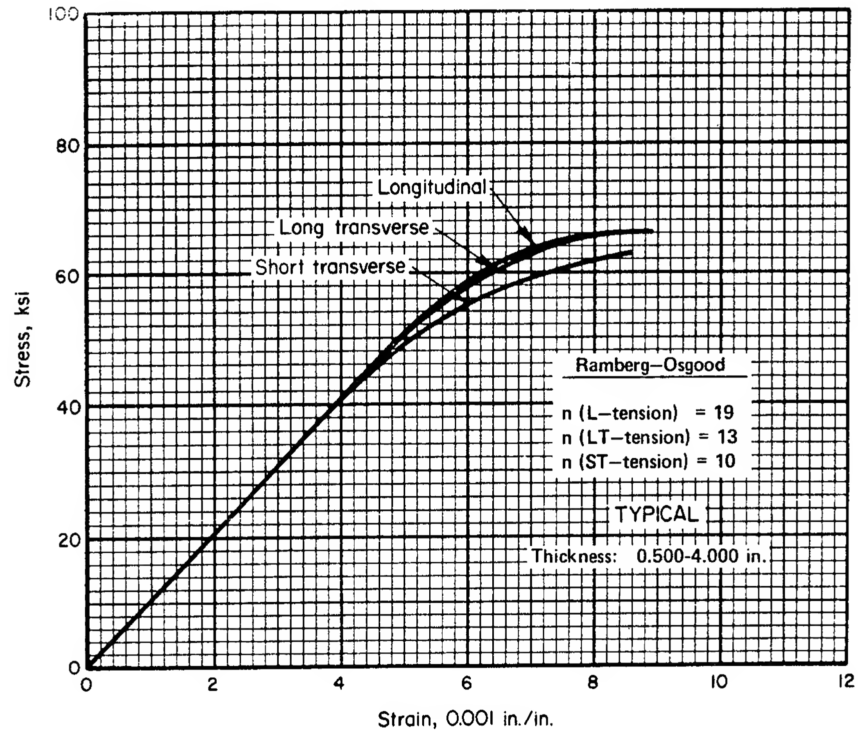

FIGURE 3.7.3.2.6(a). *Typical tensile stress-strain curves for 7050-T7451 aluminum alloy plate at room temperature.*

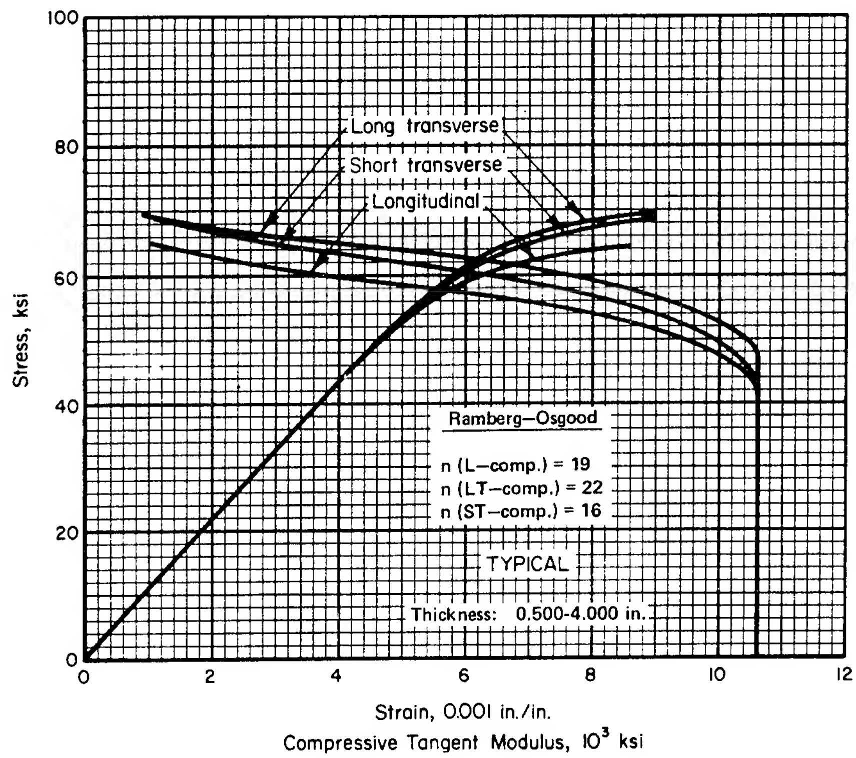

FIGURE 3.7.3.2.6(b). *Typical compressive stress-strain and compressive tangent-modulus curves for 7050-T7451 aluminum alloy plate at room temperature.*

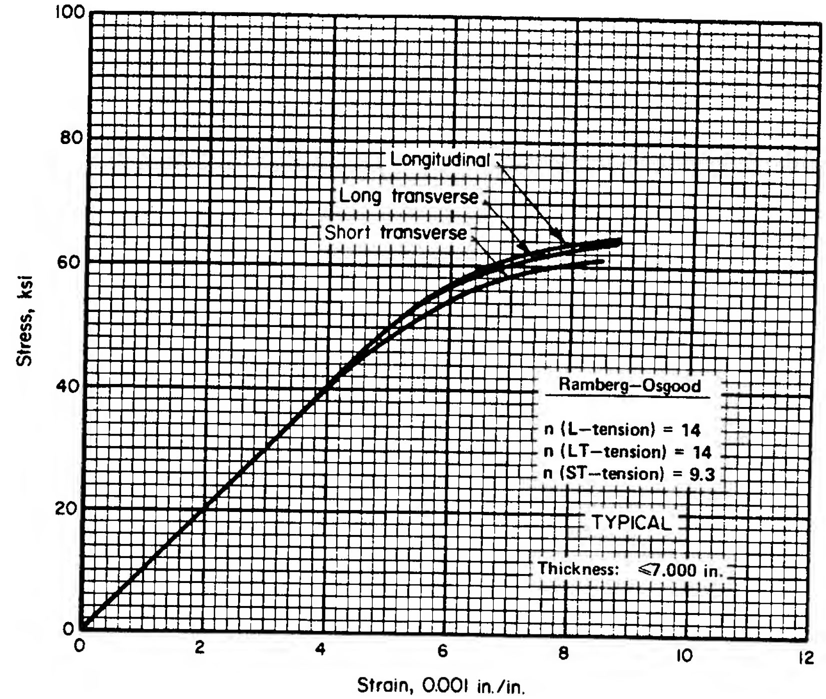

FIGURE 3.7.3.2.6(c). *Typical tensile stress-strain curves for 7050-T7452 aluminum alloy hand forging at room temperature.*

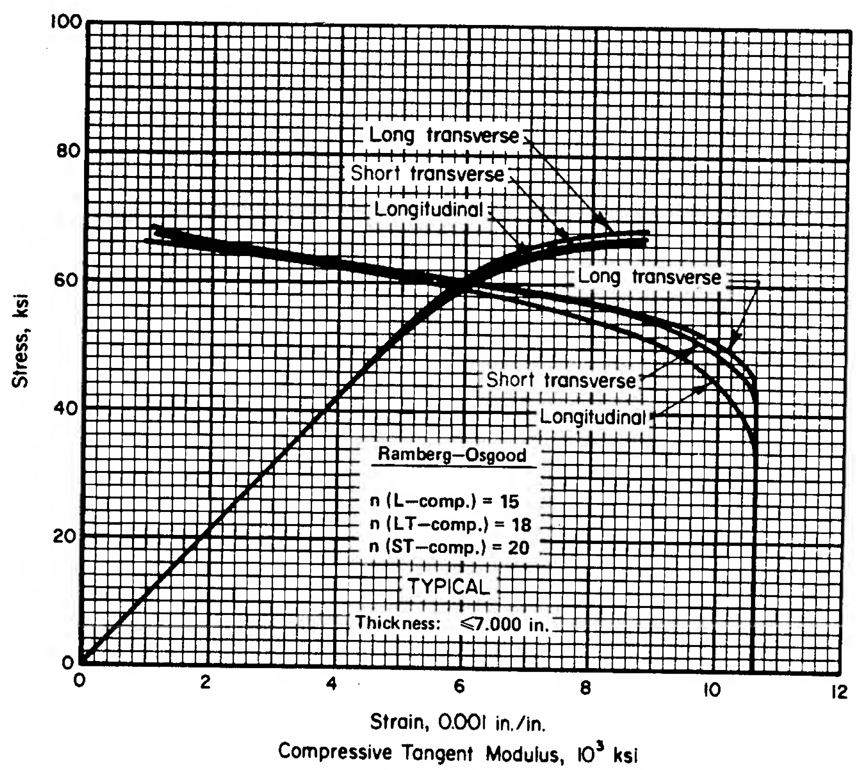

FIGURE 3.7.3.2.6(d). *Typical compressive stress-strain and compressive tangent-modulus curves for 7050-T7452 aluminum alloy hand forging at room temperature.*

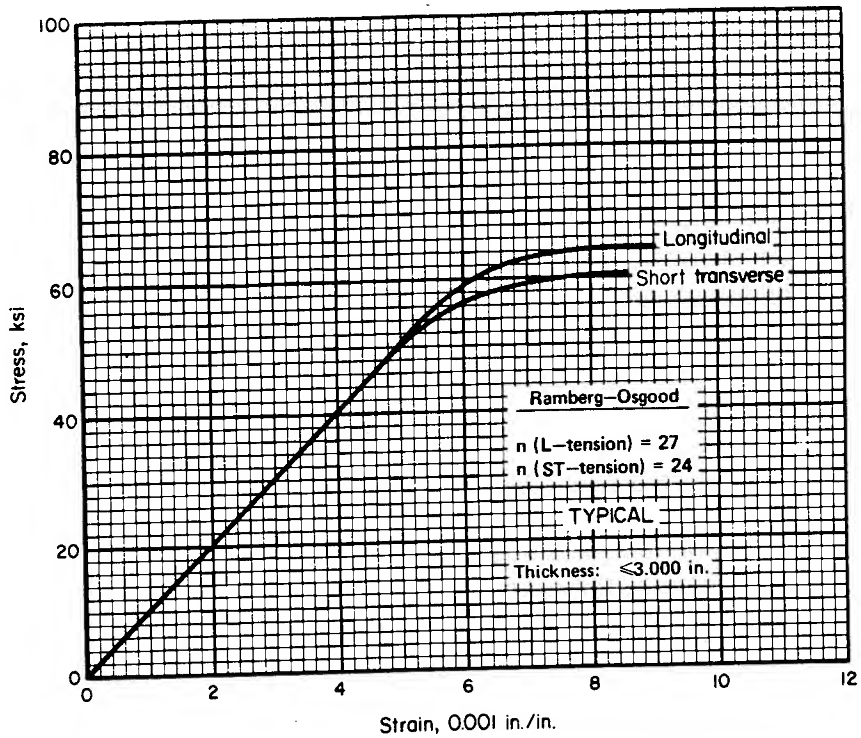

FIGURE 3.7.3.2.6(e). *Typical tensile stress-strain curves for 7050-T74 aluminum alloy die forging at room temperature.*

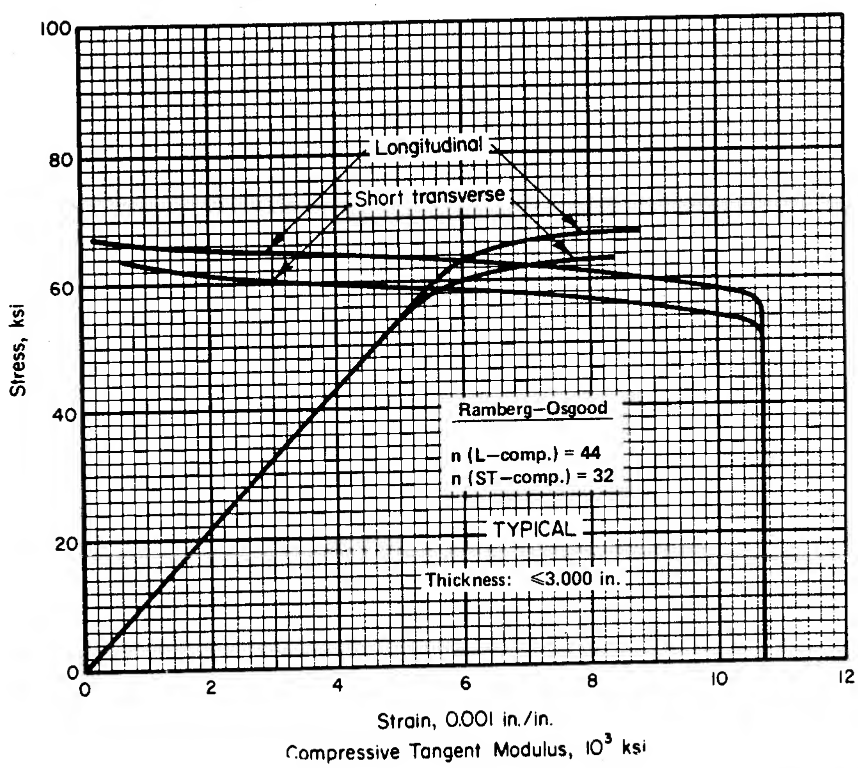

FIGURE 3.7.3.2.6(f). *Typical compressive stress-strain and compressive tangent-modulus curves for 7050-T74 aluminum alloy die forging at room temperature.*

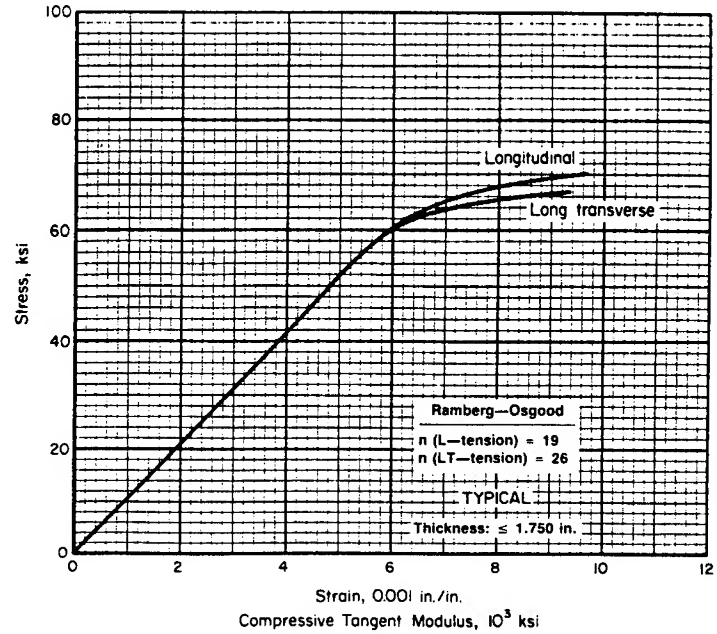

FIGURE 3.7.3.2.6(g). *Typical tensile stress-strain curves for 7050-T74511 aluminum alloy extrusion at room temperature.*

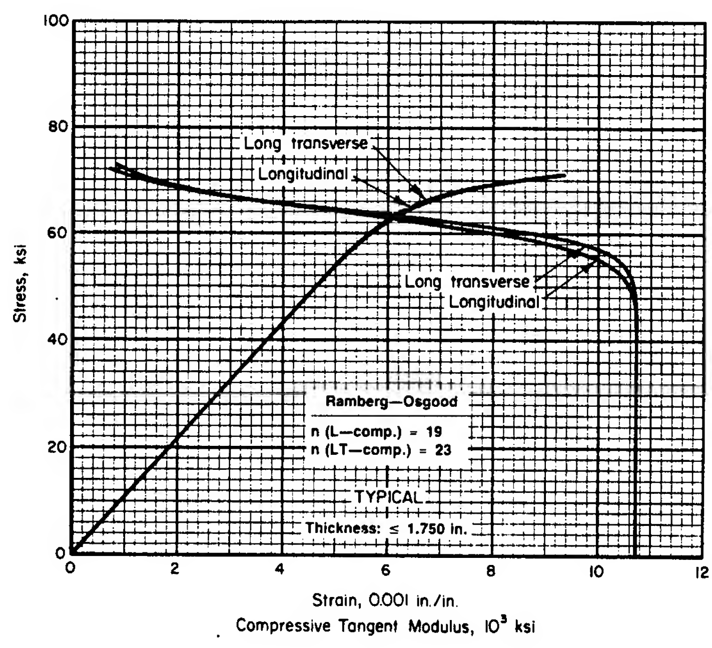

FIGURE 3.7.3.2.6(h). *Typical compressive stress-strain and tangent modulus curves for 7050-T74511 aluminum alloy extrusion at room temperature.*

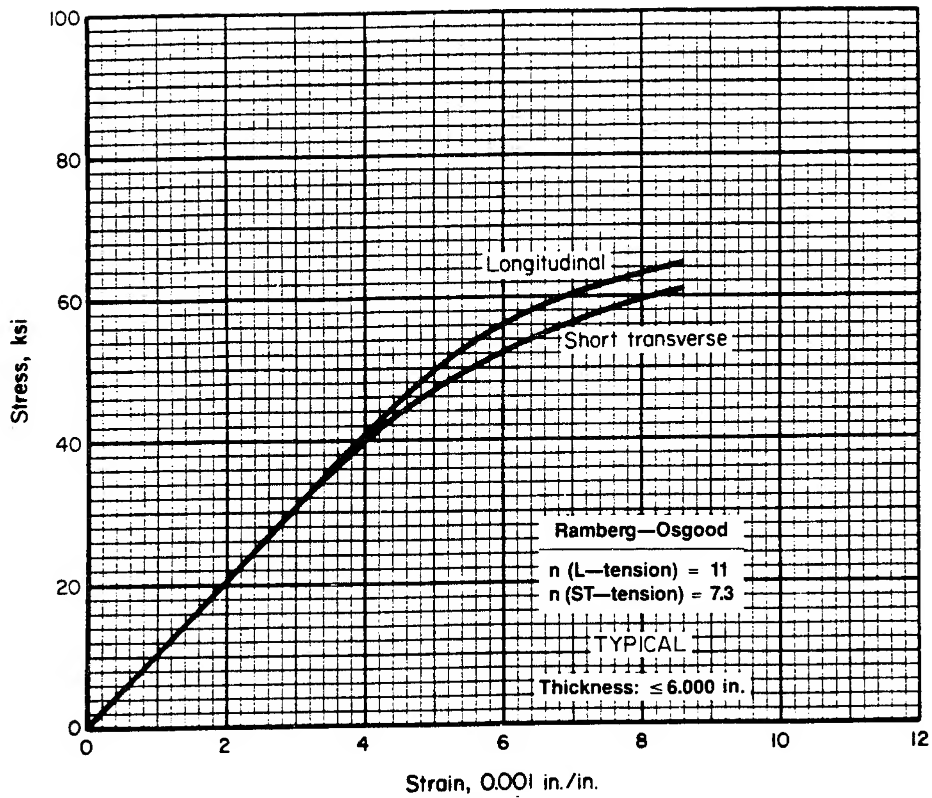

FIGURE 3.7.3.2.6(i). *Typical tensile stress-strain curves for 7050-T7452 aluminum alloy die forging at room temperature.*

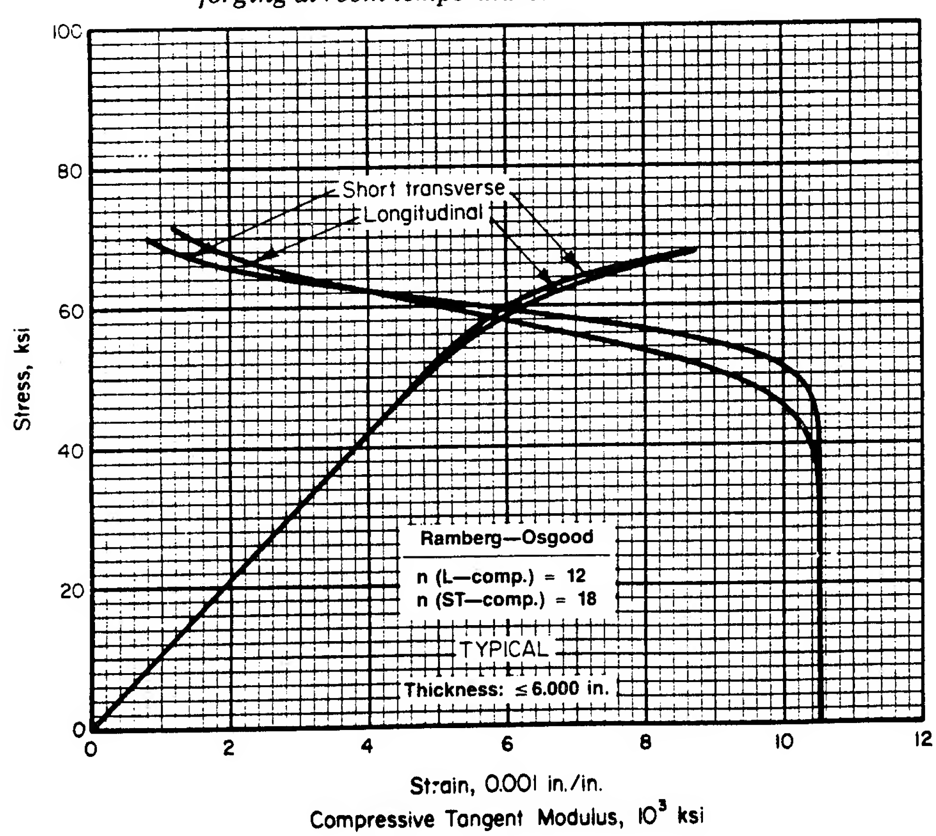

FIGURE 3.7.3.2.6(j). *Typical compressive stress-strain and tangent-modulus curves for 7050-T7452 aluminum alloy die forging at room temperature.*

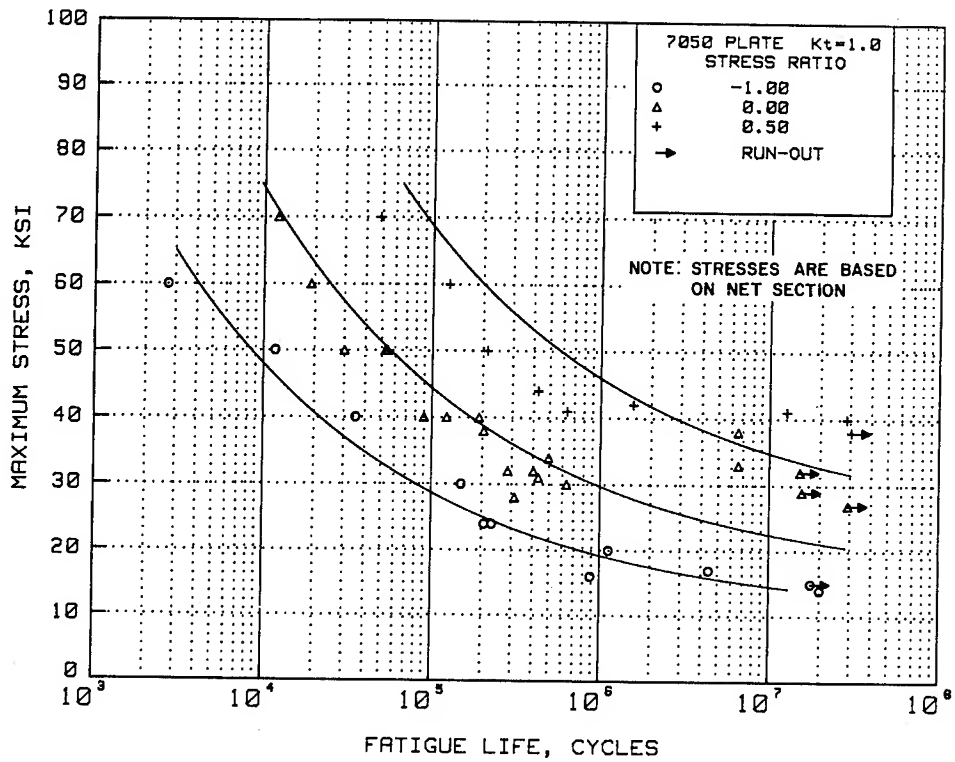

FIGURE 3.7.3.2.8(a). *Best-fit S/N curves for unnotched 7050-T7451 plate, longitudinal direction.*

Correlative Information for Figure 3.7.3.2.8(a)

Product Form: Plate, 1.0-inch thick

Properties:	TUS, ksi	TYS, ksi	Temp.,F
	79	72	RT

Specimen Details: Unnotched
0.300-inch diameter

Surface Condition: Not specified

Reference: 3.7.3.2.9(b) and 3.7.7.2.8(b)

Test Parameters:
Loading - Axial
Frequency - 800 cpm
Temperature - RT
Environment - Air

No. of Heats/Lots: 10

Equivalent Stress Equation:
Log N_f=9.73-3.24 log ($S_{eq}-15.5$)
$S_{eq}=S_{max}(1-R)^{0.63}$
Standard Error of Estimate=0.490
Standard Deviation in Life=0.942
R^2=73%

Sample Size=35

(Caution: The equivalent stress model may provide unrealistic life predictions for stress ratios beyond those represented above.)

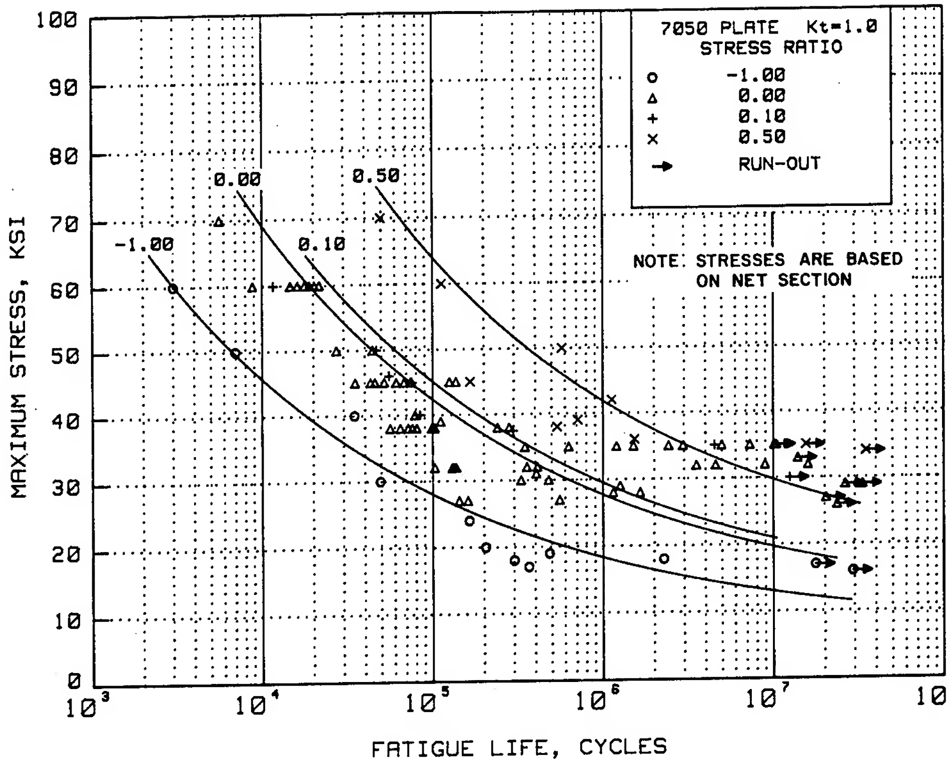

FIGURE 3.7.3.2.8(b). *Best-fit S/N curves for unnotched 7050-T7451 plate, long transverse direction.*

Correlative Information for Figure 3.7.3.2.8(b)

Product Form: Plate, 1.0-6.0 inches thick

Properties:	TUS, ksi	TYS, ksi	Temp.,F
	73-81	62-72	RT

Specimen Details: Unnotched
0.250 and 0.300-inch diameter

Surface Condition: Not specified

Reference: 3.7.3.2.9(b), 3.7.7.2.8(b) and (c)

Test Parameters:
Loading - Axial
Frequency - 800 cpm and unspecified
Temperature - RT
Environment - Air

No. of Heats/Lots: 15

Equivalent Stress Equation:
Log N_f=10.7-3.81 log (S_{eq}−10)
$S_{eq}=S_{max}(1-R)^{0.59}$
Standard Error of Estimate=0.507
Standard Deviation in Life=0.794
R^2=59%

Sample Size=85

(Caution: The equivalent stress model may provide unrealistic life predictions for stress ratios beyond those represented above.)

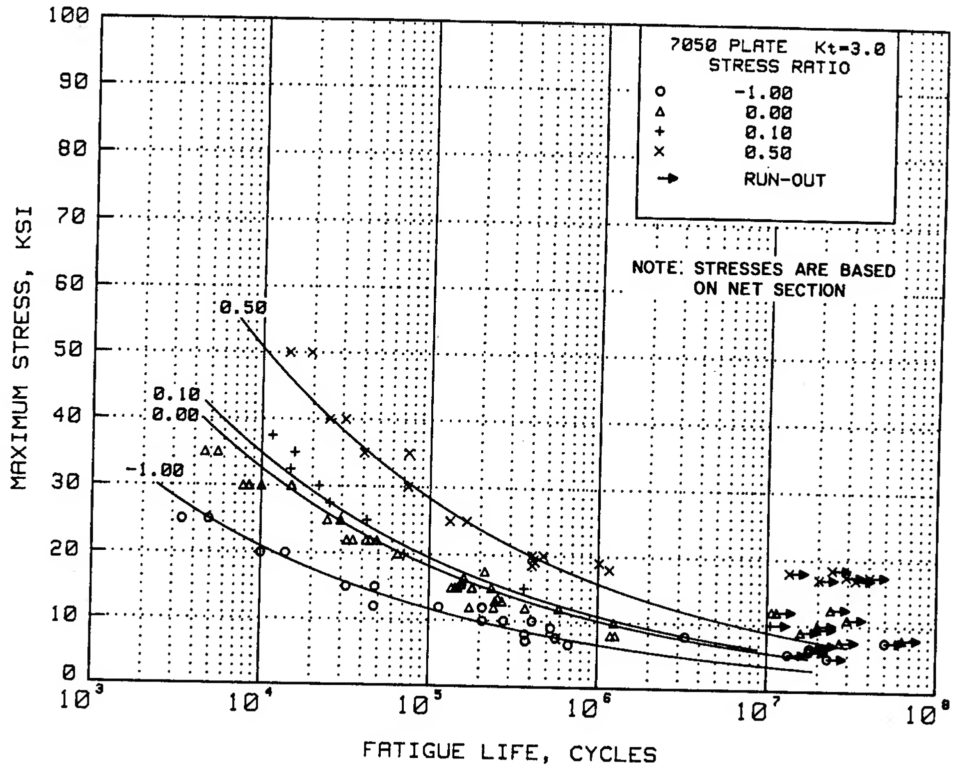

FIGURE 3.7.3.2.8(c). *Best-fit S/N curves for notched, K_t = 3.0, 7050-T7451 plate, longitudinal and long transverse direction.*

Correlative Information for Figure 3.7.3.2.8(c)

Product Form: Plate, 1.0-6.0-inches thick

Properties:

TUS, ksi	TYS, ksi	Temp.,F
75-81	65-72	RT

Specimen Details: Circumferentially notched, K_t=3.0
0.306 and 0.373-inch gross diameter
0.253-inch net diameter
0.013-inch notch-tip radius, r
60° flank angle, ω

Surface Condition: Not specified

Reference: 3.7.3.2.9(b), 3.7.7.2.8(b) and (c)

Test Parameters:
Loading - Axial
Frequency - 800 cpm and unspecified
Temperature - RT
Environment - Air

No. of Heats/Lots: 11

Equivalent Stress Equation:
$\text{Log } N_f = 10.0 - 3.96 \log (S_{eq})$
$S_{eq} = S_{max}(1-R)^{0.64}$
Standard Error of Estimate=0.248
Standard Deviation in Life=0.728
R^2=88%

Sample Size=79

(Caution: The equivalent stress model may provide unrealistic life predictions for stress ratios beyond those represented above.)

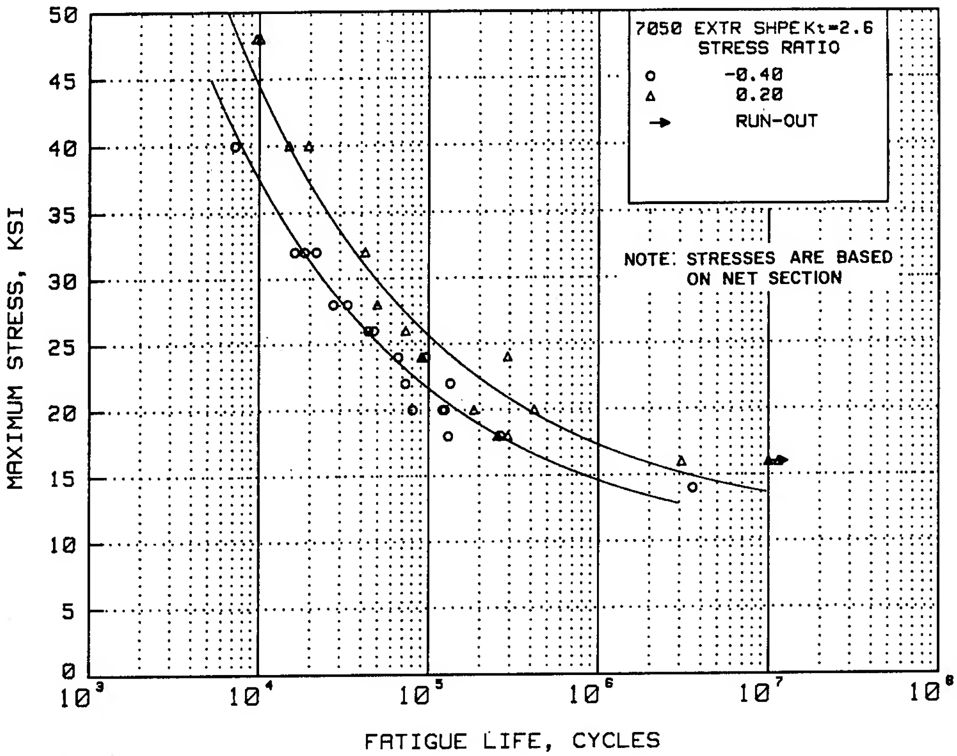

FIGURE 3.7.3.2.8(d). *Best-fit S/N curve for notched, K_t = 2.6, 7050-T7451X extruded shape, longitudinal direction.*

Correlative Information for Figure 3.7.3.2.8(d)

Product Form: Extruded shape, 0.5-5.0-inch thick

Properties:	TUS, ksi	TYS, ksi	Temp.,F
	76-77	67-68	RT

Specimen Details: Notched, center hole K_t=2.6
0.150-inch diameter
0.250-inch thick
1.00-inch wide

Surface Condition: Not specified

Reference: 3.7.3.2.8(a)

Test Parameters:
Loading - Axial
Frequency - Not specified
Temperature - RT
Environment - Air

No. of Heats/Lots: 6

Equivalent Stress Equation:
Log N_f=8.23-2.82 log ($S_{eq}-10$)
$S_{eq}=S_{max}(1-R)^{0.30}$
Standard Error of Estimate=0.243
Standard Deviation in Life=0.724
R^2=89%

Sample Size=34

(Caution: The equivalent stress model may provide unrealistic life predictions for stress ratios beyond those represented above.)

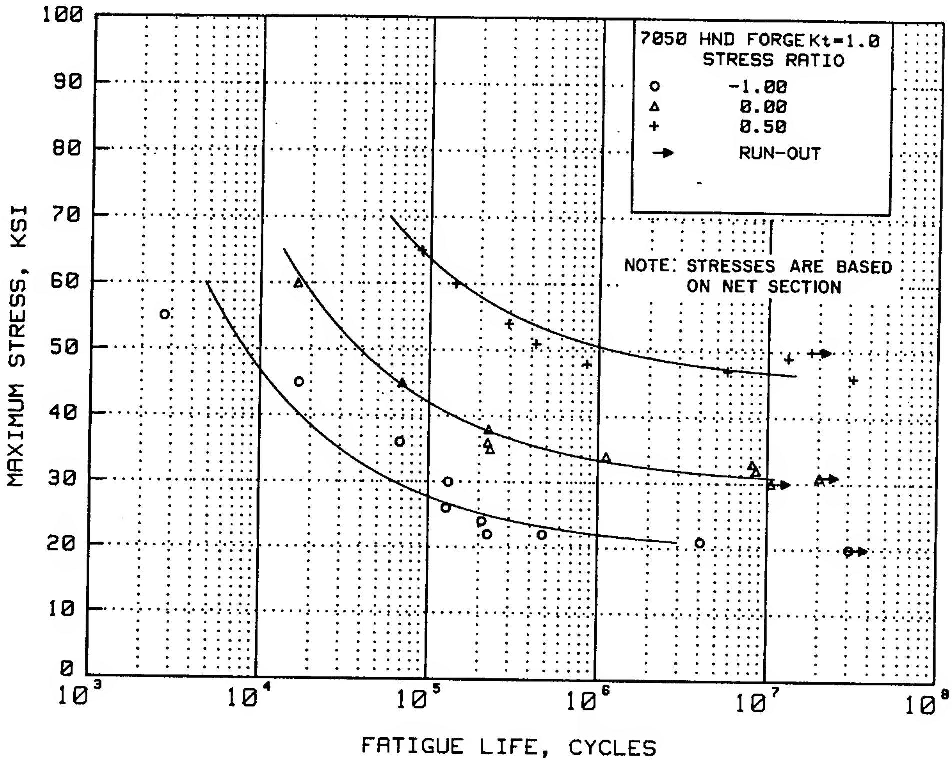

FIGURE 3.7.3.2.8(e). *Best-fit S/N curves for unnotched 7050-T7452 hand forgings, longitudinal direction.*

Correlative Information for Figure 3.7.3.2.8(e)

Product Form: Hand forgings, 2.0-8.0-inch thick

Properties:	TUS, ksi	TYS, ksi	Temp.,F
	76-81	66-72	RT

Specimen Details: Unnotched
0.300-inch diameter

Surface Condition: Not specified

Reference: 3.7.3.2.9(b) and 3.7.6.2.8(b)

Test Parameters:
Loading - Axial
Frequency - 800 cpm
Temperature - RT
Environment - Air

No. of Heats/Lots: 10

Equivalent Stress Equation:
Log N_f=7.06−1.89 log (S_{eq}−30)
$S_{eq}=S_{max}(1-R)^{0.60}$
Standard Error of Estimate=0.400
Standard Deviation in Life=0.982
R^2=83%

Sample Size=25

(Caution: The equivalent stress model may provide unrealistic life predictions for stress ratios beyond those represented above.)

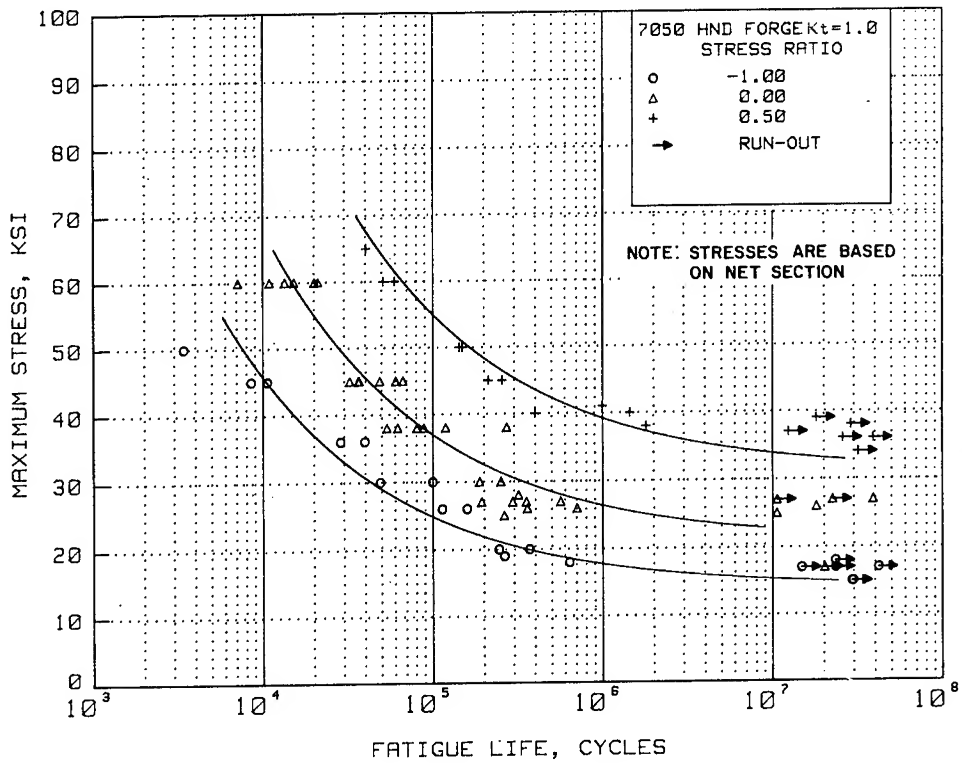

FIGURE 3.7.3.2.8(f). *Best-fit S/N curves for unnotched 7050-T7452 hand forgings, long transverse and short transverse directions.*

Correlative Information for Figure 3.7.3.2.8(f)

Product Form: Hand forgings, 2.0-8.0-inch thick

Properties:

TUS, ksi	TYS, ksi	Temp.,F
73-80	59-70	RT

Specimen Details: Unnotched
0.300-inch diameter

Surface Condition: Not specified

Reference: 3.7.3.2.9(b) and 3.7.7.2.8(b)

Test Parameters:
Loading - Axial
Frequency - 800 cpm
Temperature - RT
Environment - Air

No. of Heats/Lots: 10

Equivalent Stress Equation:
Log N_f=7.58-2.14 log ($S_{eq}-21$)
$S_{eq}=S_{max}(1-R)^{0.57}$
Standard Error of Estimate=0.400
Standard Deviation in Life=0.803
R^2=75%

Sample Size=55

(Caution: The equivalent stress model may provide unrealistic life predictions for stress ratios beyond those represented above.)

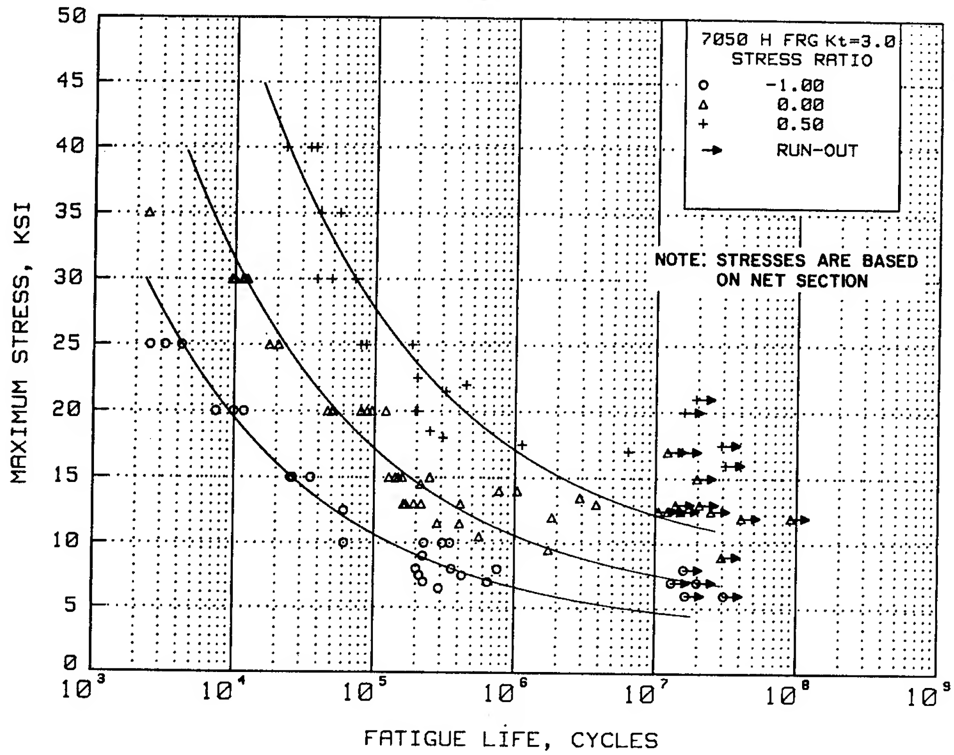

FIGURE 3.7.3.2.8(g). *Best-fit S/N curves for notched, K_t = 3.0, 7050-T7452 hand forgings, longitudinal, long transverse and short transverse directions.*

Correlative Information for Figure 3.7.3.2.8(g)

Product Form: Hand forgings, 2.0-8.0-inch thick

Properties:	TUS, ksi	TYS, ksi	Temp.,F
	73-81	59-72	RT

Specimen Details: Circumferentially notched, K_t=3.0
0.306-inch gross diameter
0.253-inch net diameter
0.013-inch root radius, r
60° flank angle, ω

Surface Condition: Not specified

Reference: 3.7.3.2.9(b) and 3.7.7.2.8(b)

Test Parameters:
Loading - Axial
Frequency - 800 cpm
Temperature - RT
Environment - Air

No. of Heats/Lots: 10

Equivalent Stress Equation:
Log N_f=8.21-2.96 log (S_{eq}−5)
$S_{eq}=S_{max}(1-R)^{0.68}$
Standard Error of Estimate=0.307
Standard Deviation in Life=0.735
R^2=83%

Sample Size=80

(Caution: The equivalent stress model may provide unrealistic life predictions for stress ratios beyond those represented above.)

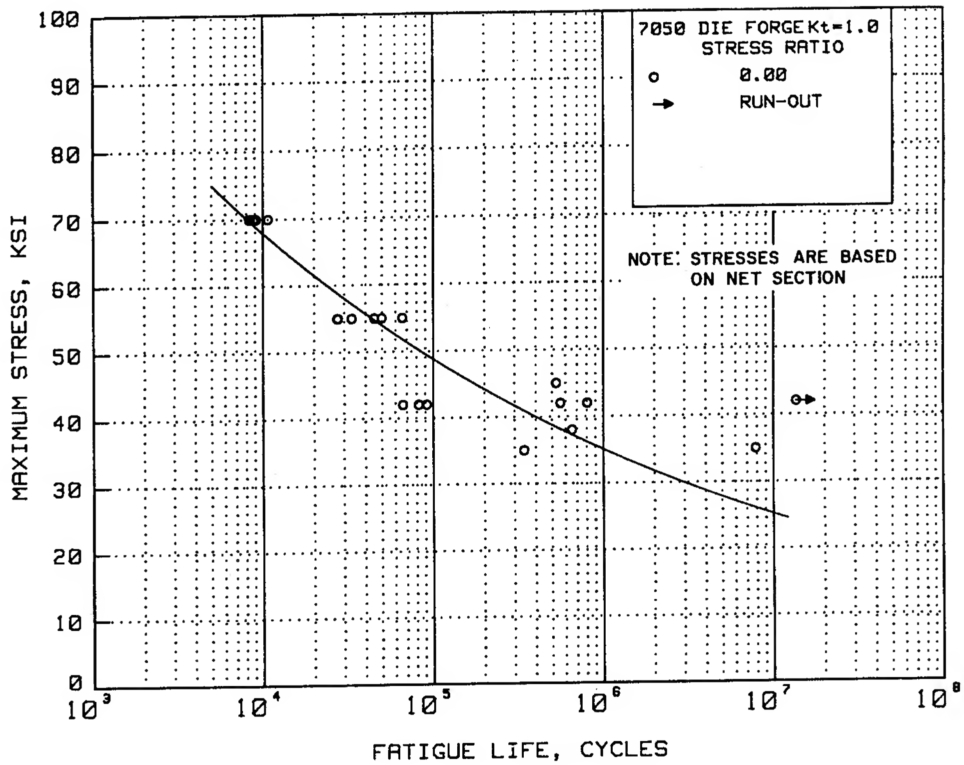

FIGURE 3.7.3.2.8(h). *Best-fit S/N curve for unnotched 7050-T74 die forging, longitudinal direction.*

Correlative Information for Figure 3.7.3.2.8(h)

Product Form: Die forging

Properties:	TUS, ksi	TYS, ksi	Temp.,F
	74-81	68-71	RT

Specimen Details: Unnotched,
0.300 inch diameter

Surface Condition: Not specified

Reference: 3.7.3.2.9(b) and 3.7.7.2.8(b)

Test Parameters:
Loading - Axial
Frequency - 800 cpm
Temperature - RT
Environment - Air

No. of Heats/Lots: 4

Equivalent Stress Equation:
Log N_f=16.8-6.97 log (S_{max})
Standard Error of Estimate=0.381
Standard Deviation in Life=0.820
R^2=78%

Sample Size=20

(Caution: The equivalent stress model may provide unrealistic life predictions for stress ratios beyond those represented above.)

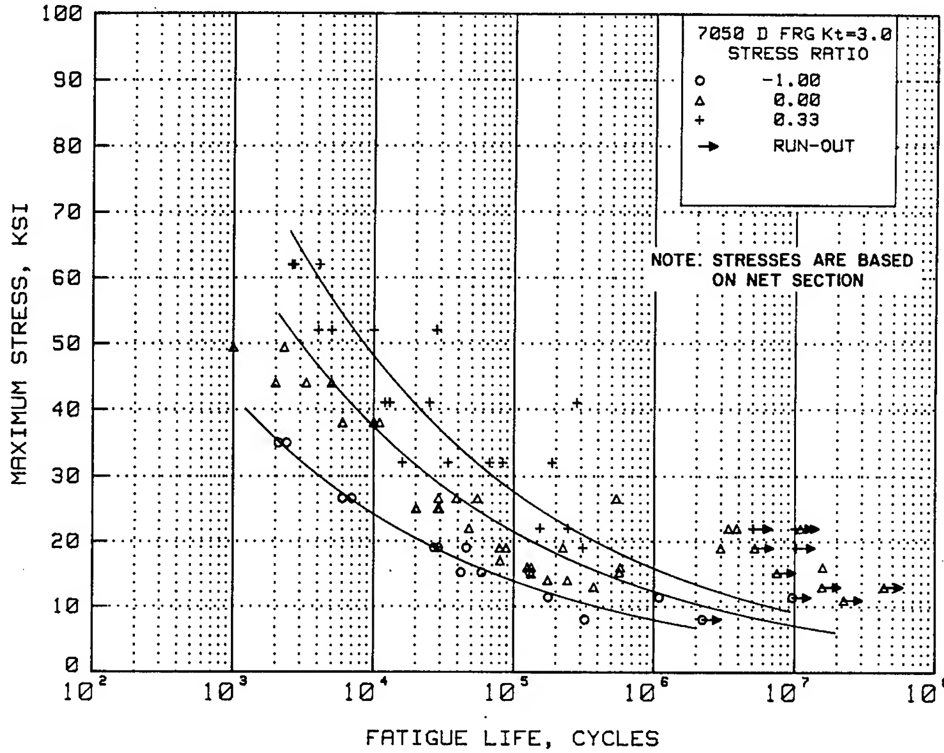

FIGURE 3.7.3.2.8(i). *Best-fit curves for notched, K_t = 3.0, 7050-T74 die forging, longitudinal direction.*

Correlative Information for Figure 3.7.3.2.8(i)

Product Form: Die forging

Properties:	TUS, ksi	TYS, ksi	Temp.,F
	77-81	68-71	RT

Specimen Details: Circumferentially notched, K_t=3.0
0.306 or 0.305-inch gross diameter
0.253 or 0.222-inch net diameter
0.013 or 0.012-inch root radius, r
60° flank angle, ω

Surface Condition: Not specified

Reference: 3.7.3.2.8(b), 3.7.3.2.9(b), and 3.7.7.2.8(b)

Test Parameters:
Loading - Axial
Frequency - 800, 1800 cpm
Temperature - RT
Environment - Air

No. of Heats/Lots: 6

Equivalent Stress Equation:
$\text{Log } N_f = 10.5 - 4.14 \log (S_{eq})$
$S_{eq} = S_{max}(1-R)^{0.629}$
Standard Error of Estimate=0.506
Standard Deviation in Life=0.896
R^2=68%

Sample Size=73

(Caution: The equivalent stress model may provide unrealistic life predictions for stress ratios beyond those represented above.)

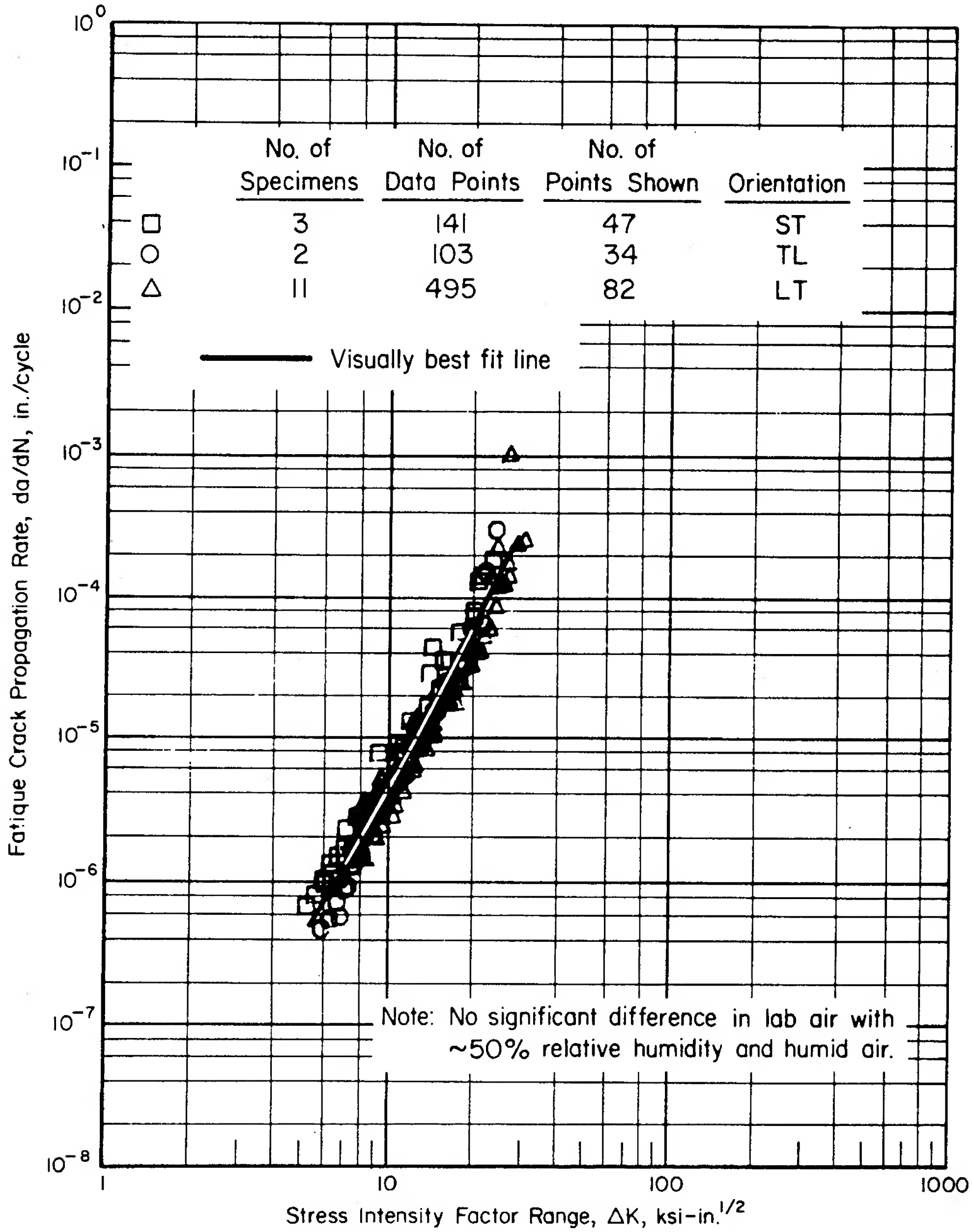

FIGURE 3.7.3.2.9(a). *Fatigue-crack-propagation data for 6-inch-thick 7050-T7451 aluminum plate. [Reference 3.7.3.2.9(a).]*

Specimen Thickness:	*0.499-0.500 inch*	*Environment:*	*Lab air (~50% humidity) and humid air (100% humidity)*
Specimen Width:	*2.989-3.000 inches*		
Specimen Type:	*CT*	*Temperature:*	*RT*
Stress Ratio, R:	*0.1*	*Frequency, f:*	*10-20 Hz*

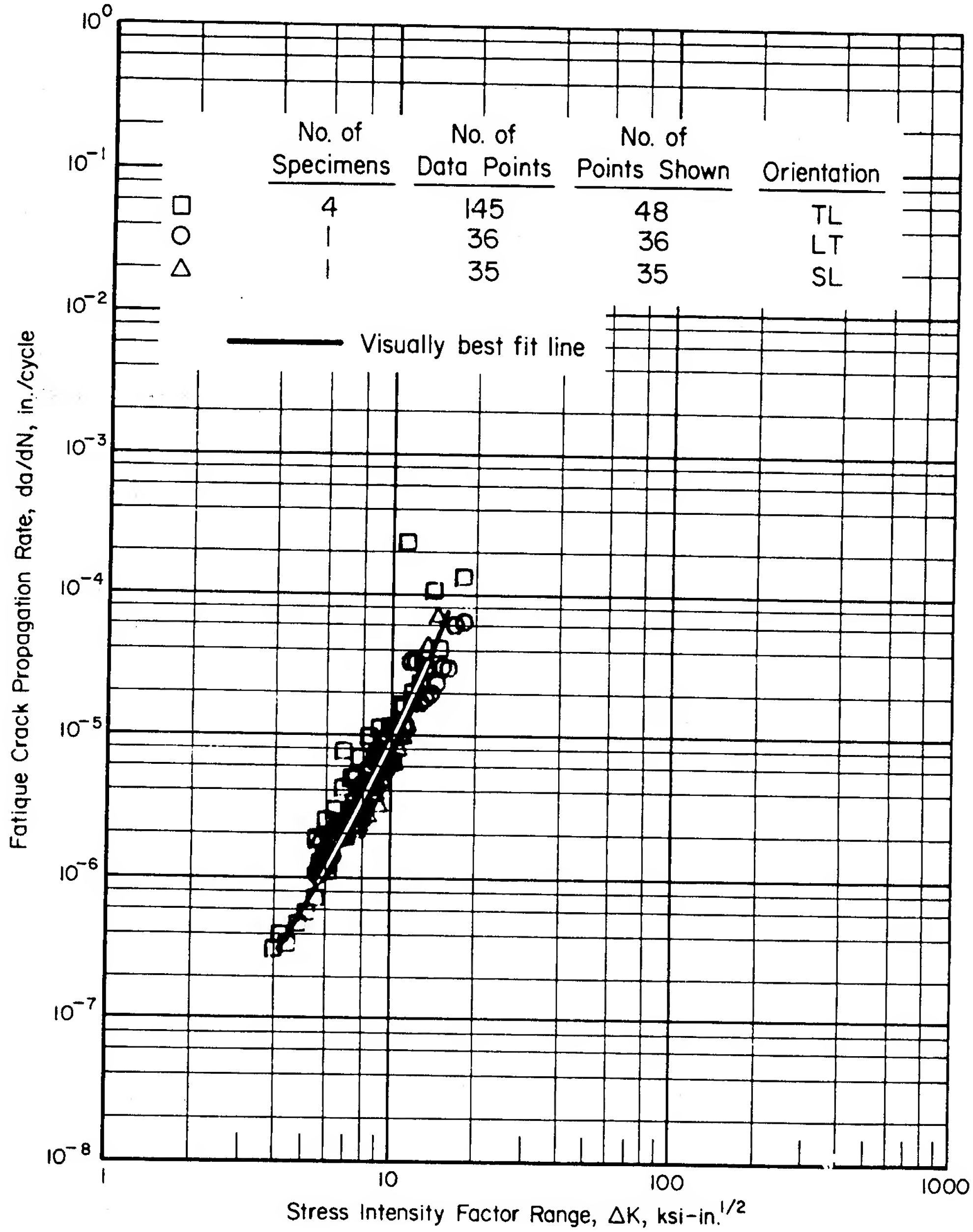

FIGURE 3.7.3.2.9(b). *Fatigue-crack-propagation data for 1- and 6-inch-thick 7050-T7451 aluminum plate. [Reference 3.7.3.2.9(b).]*

Specimen Thickness:	*0.999–1.000 inch*	*Environment:*	*Dry air (<10% humidity)*
Specimen Width:	*3.805 inches*	*Temperature:*	*RT*
Specimen Type:	*CT*	*Frequency, f:*	*18.3 Hz*
Stress Ratio, R:	*0.33*		

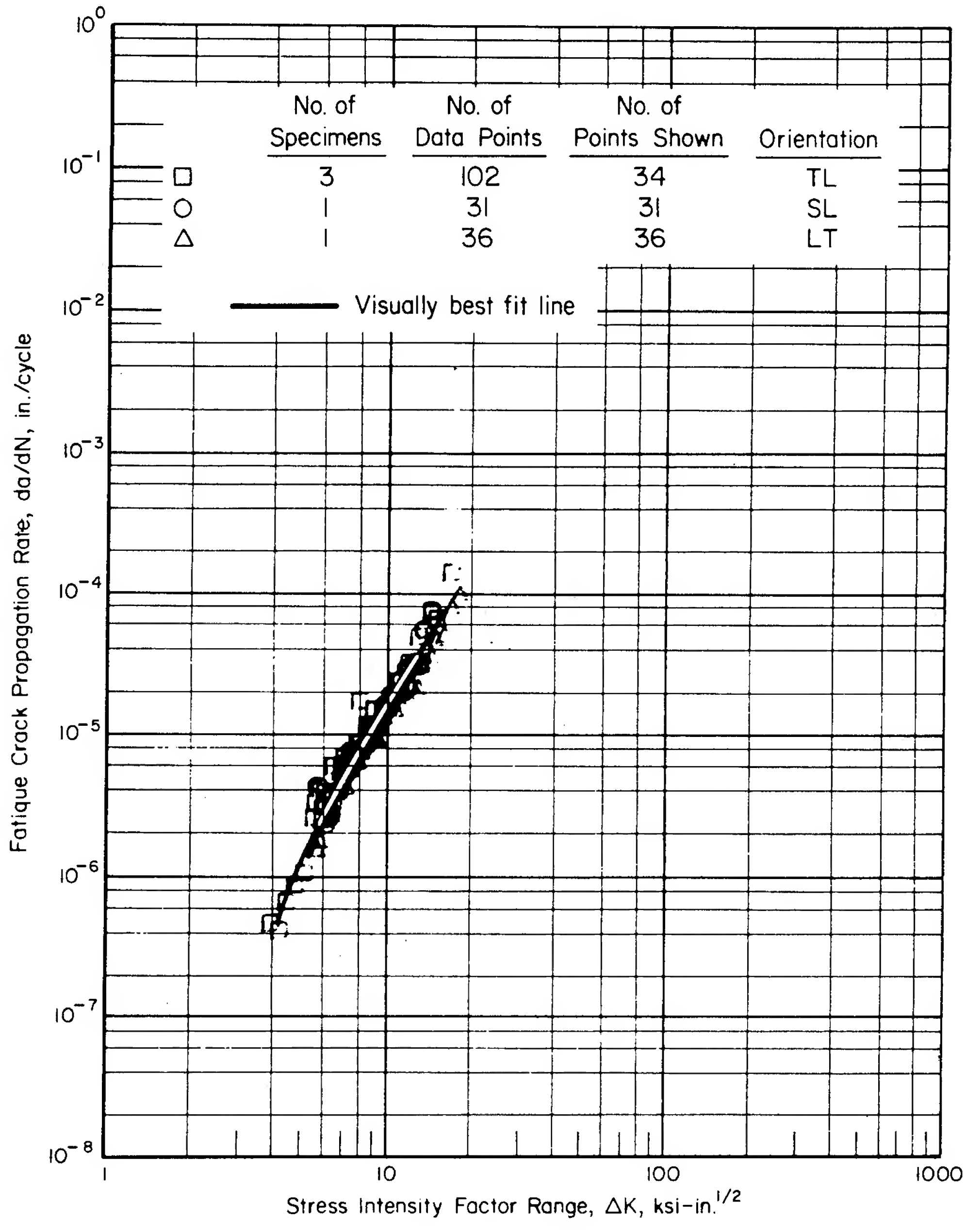

FIGURE 3.7.3.2.9(c). *Fatigue-crack-propagation data for 1- and 6-inch-thick 7050-T7451 aluminum plate.* [*Reference 3.7.3.2.9(b).*]

Specimen Thickness:	*0.998-1.000 inch*	*Environment:*	*Humid air (>90% humidity)*
Specimen Width:	*3.805 inches*	*Temperature:*	*RT*
Specimen Type:	*CT*	*Frequency, f:*	*18.3 Hz*
Stress Ratio, R:	*0.33*		

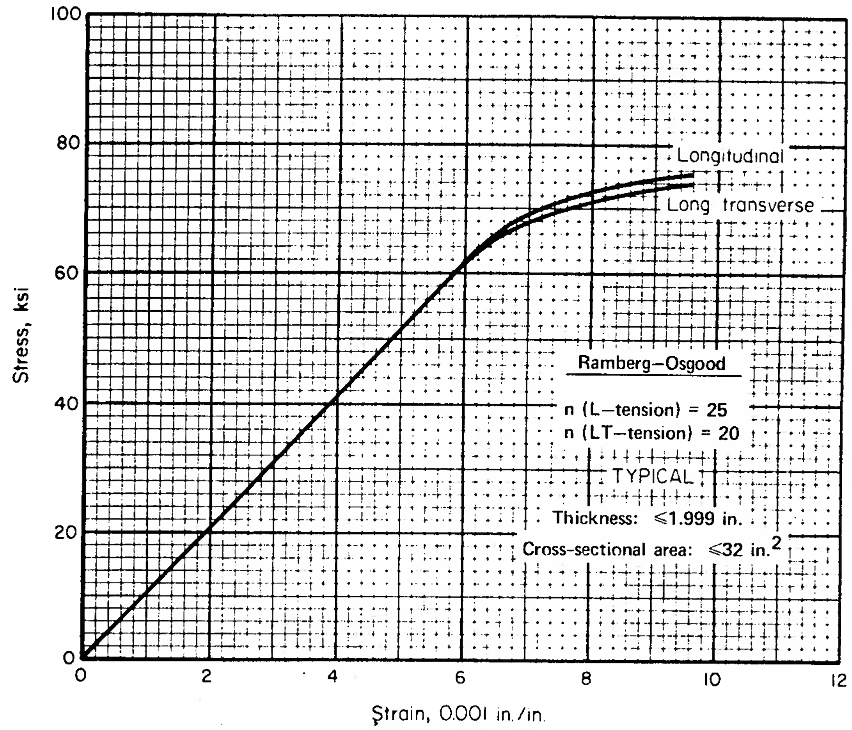

FIGURE 3.7.3.3.6(a). *Typical tensile stress-strain curves for 7050-T7651X aluminum alloy extrusion at room temperature.*

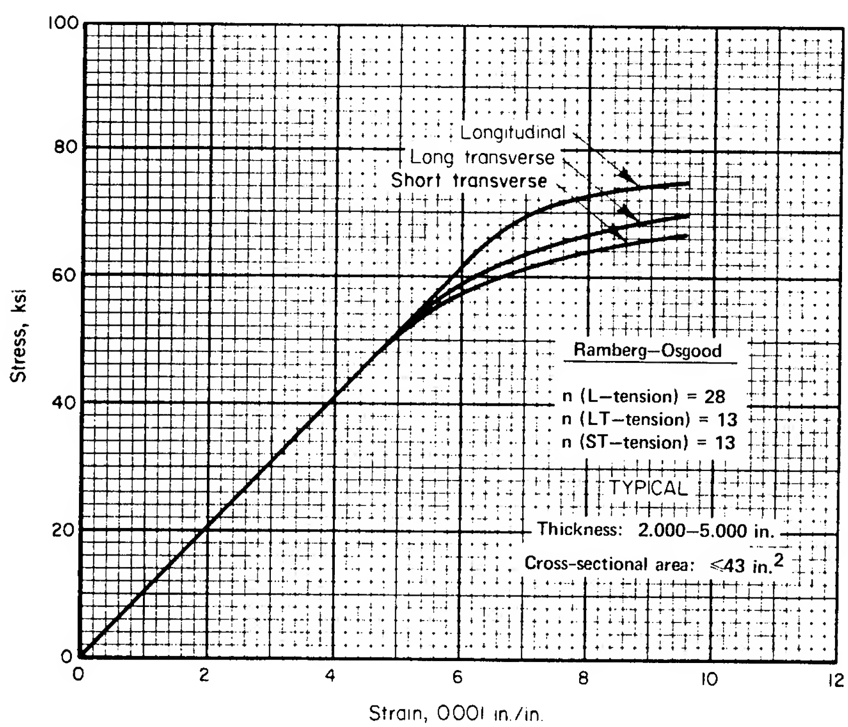

FIGURE 3.7.3.3.6(b). *Typical tensile stress-strain curves for 7050-T7651X aluminum alloy extrusion at room temperature.*

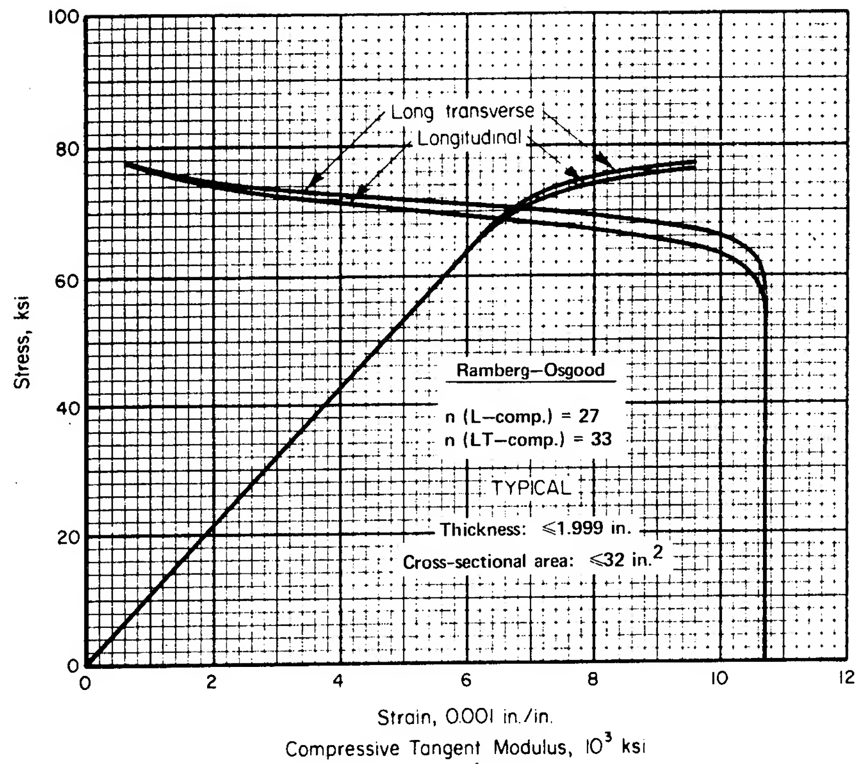

FIGURE 3.7.3.3.6(c). *Typical compressive stress-strain and compressive tangent-modulus curves for 7050-T7651X aluminum alloy extrusion at room temperature.*

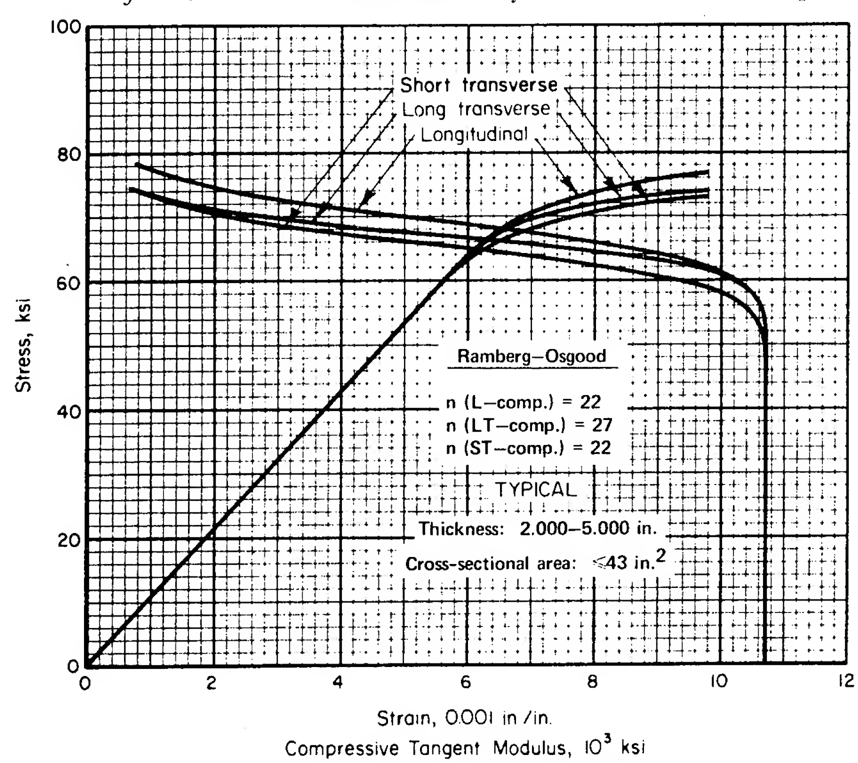

FIGURE 3.7.3.3.6(d). *Typical compressive stress-strain and compressive tangent-modulus curves for 7050-T7651X aluminum alloy extrusion at room temperature.*

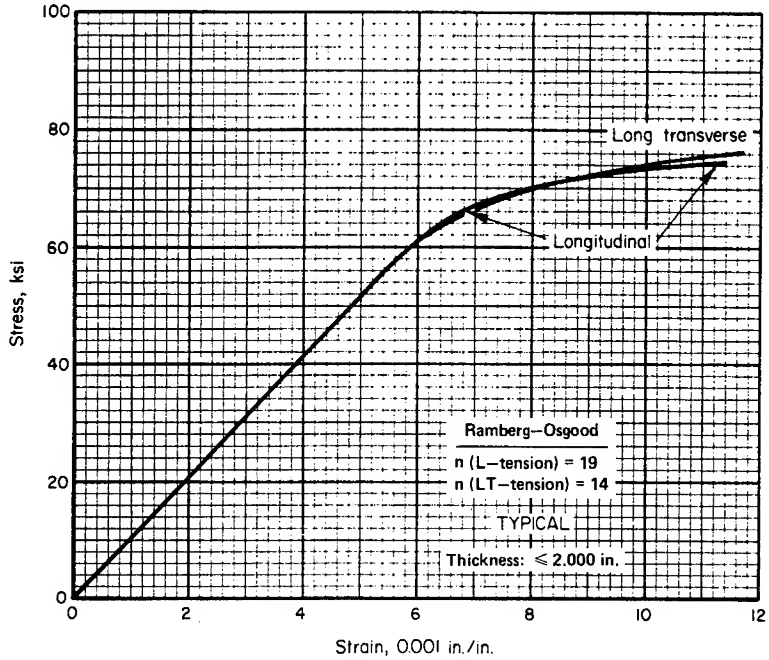

FIGURE 3.7.3.3.6(e). *Typical tensile stress-strain curves for 7050-T7651 aluminum alloy plate at room temperature.*

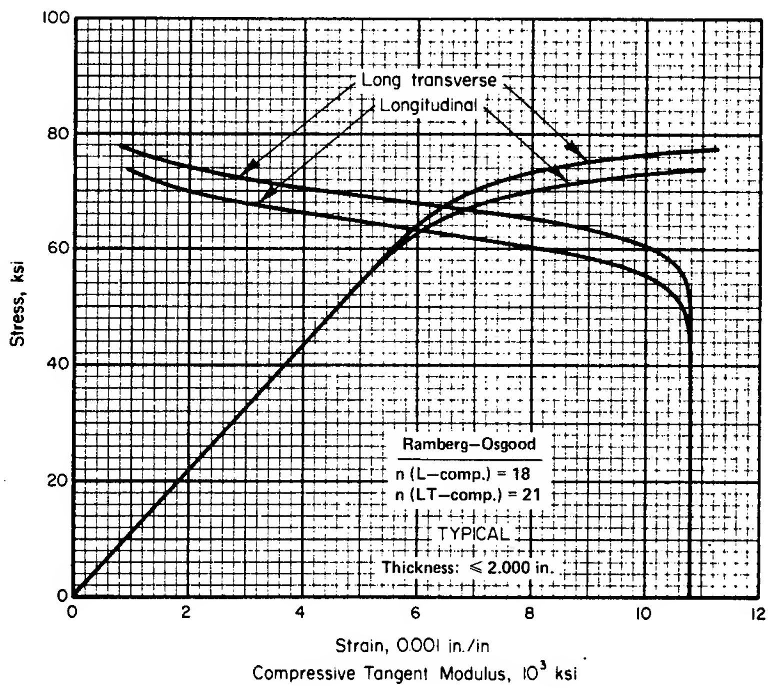

FIGURE 3.7.3.3.6(f). *Typical compressive stress-strain and compressive tangent-modulus curves for 7050-T7651 aluminum alloy plate at room temperature.*

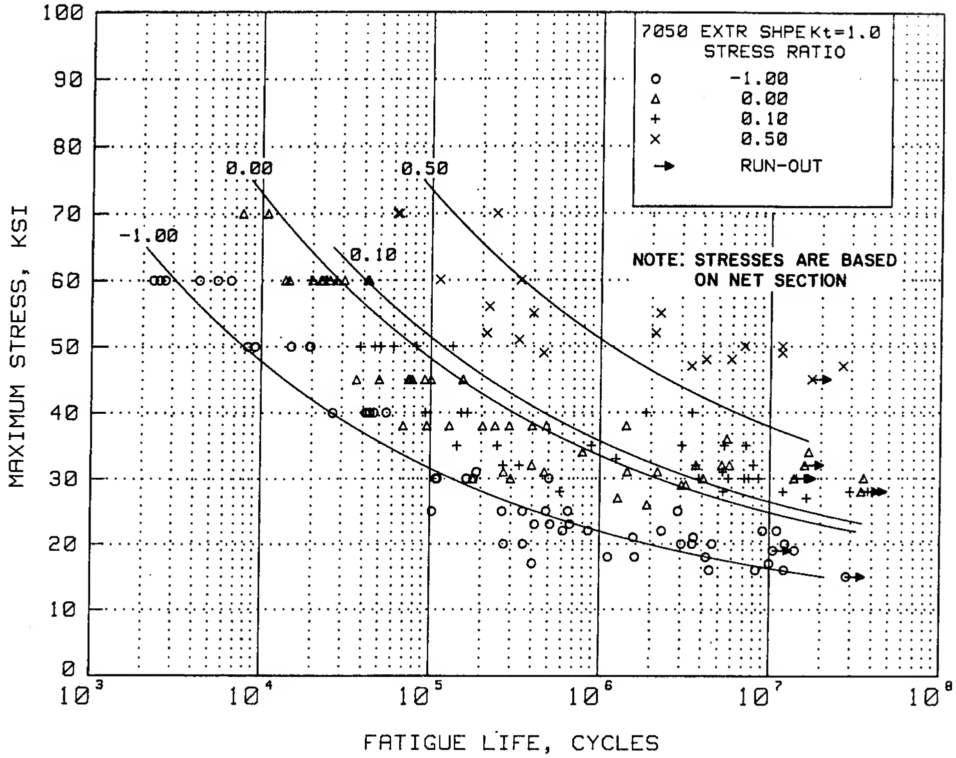

FIGURE 3.7.3.3.8(a). *Best-fit S/N curve for unnotched 7050-T7651X extruded shape, longitudinal and long transverse directions.*

Correlative Information for Figure 3.7.3.3.8(a)

Product Form: Extruded shape, 0.5-5.0-inch thick

Properties:	TUS, ksi	TYS, ksi	Temp.,F
	84-90	75-81	RT

Specimen Details: Unnotched, 0.300-inch diameter

Surface Condition: Not specified

Reference: 3.7.3.2.9(b), 3.7.3.3.8(a), and 3.7.7.2.8(b)

Test Parameters:
Loading - Axial
Frequency - 800, cpm
Temperature - RT
Environment - Air

No. of Heats/Lots: 10

Equivalent Stress Equation:
Log N_f=11.8-4.38 log (S_{eq}-12)
$S_{eq}=S_{max}(1-R)^{0.61}$
Standard Error of Estimate=0.493
Standard Deviation in Life=1.01
R^2=76%

Sample Size=161

(Caution: The equivalent stress model may provide unrealistic life predictions for stress ratios beyond those represented above.)

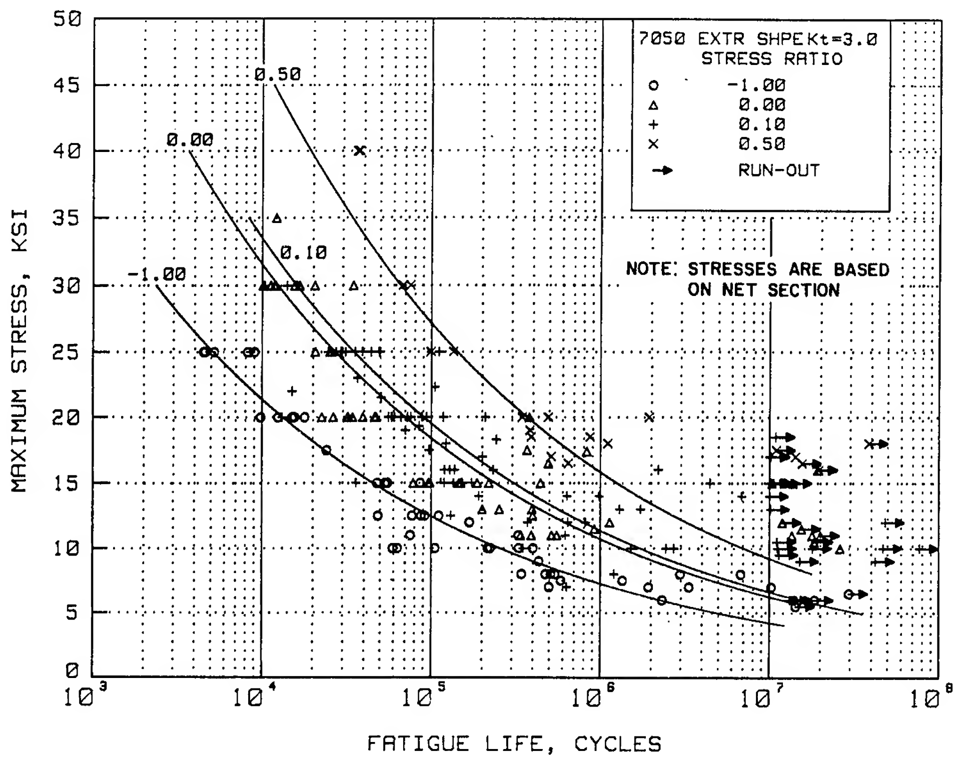

FIGURE 3.7.3.3.8(b). *Best-fit S/N curve for notched, K_t = 3.0, 7050-T7651X extruded shape, longitudinal and long transverse directions.*

Correlative Information for Figure 3.7.3.3.8(b)

Product Form: Extruded shape, 0.5-5.0-inch thick

Properties:	TUS, ksi	TYS, ksi	Temp.,F
	78-90	68-81	RT

Specimen Details: Circumferentially notched, K_t=3.0
0.359-inch gross diameter
0.253-inch net diameter
0.013-inch root radius, r
60° flank angle, ω

Surface Condition: Not specified

Reference: 3.7.3.2.9(b), 3.7.3.3.8(a), and 3.7.7.2.8(b)

Test Parameters:
Loading - Axial
Frequency - 800 cpm
Temperature - RT
Environment - Air

No. of Heats/Lots: 10

Equivalent Stress Equation:
Log N_f=8.22-2.90 log (S_{eq}-5)
$S_{eq}=S_{max}(1-R)^{0.57}$
Standard Error of Estimate=0.414
Standard Deviation in Life=0.778
R^2=72%

Sample Size=179

(Caution: The equivalent stress model may provide unrealistic life predictions for stress ratios beyond those represented above.)

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3.7.4 7075 ALLOY

3.7.4.0 *Comments and Properties.*—7075 is a high strength Al-Zn-Mg-Cu alloy and is available in a wide variety of product forms. It is also available in several types of tempers, the T6, T73, and T76 type. The T6 temper has the highest strength but lowest toughness and resistance to stress-corrosion cracking. Since toughness decreases with a decrease in temperature, the T6 temper is not generally recommended for cryogenic applications. The T73-type temper provides for much improved stress-corrosion resistance over T6-type temper with a decrease in strength. The T76-type temper provides for improved exfoliation resistance and limited stress-corrosion resistance over T6-type temper with some decrease in strength. Refer to Section 3.1.2.3 for comments regarding the resistance of the alloy to stress-corrosion cracking and to Section 3.1.3.4 for comments regarding the weldability of the alloy.

Material specifications for 7075 aluminum alloy are presented in Table 3.7.4.0(a). Room-temperature mechanical and physical properties are shown in Tables 3.7.4.0(b_1) through (g_4). The effect of temperature on the physical properties of this alloy is presented in Figure 3.7.4.0.

The temper index for 7075 is as follows:

Section	Temper
3.7.4.1	T6, T651, T652, T6510, T6511
3.7.4.2	T73, T7351, T7352, T73510, T73511

3.7.4.1 *T6, T651, T652, T6510, T6511 Temper.*—Figures 3.7.4.1.1(a) and (b) permit calculation of residual tensile strengths for complex thermal exposure conditions. They are based upon the rate parameter T(C + log t), in which T is exposure temperature in degrees Rankine, t is exposure time in hours and C is a constant evaluated for each material. These curves have been verified for use only within the ranges of temperatures and exposure times covered in the figures. The following example illustrates their use.

TABLE 3.7.4.0(a). *Material Specifications for 7075 Aluminum Alloy*

Specification	Form
AMS 4044	Bare sheet and plate
AMS 4045	Bare sheet and plate
AMS 4078	Bare plate
QQ-A-250/12, 24	Bare sheet and plate
QQ-A-250/13, 25	Clad sheet and plate
AMS 4049	Clad sheet and plate
AMS 4122	Bar and rod, rolled or cold-finished
AMS 4123	Bar and rod, rolled or cold-finished
AMS 4124	Bar and rod, rolled or cold-finished
AMS 4186	Bar and rod, rolled or cold-finished
AMS 4187	Bar and rod, rolled or cold-finished
QQ-A-225/9	Rolled or drawn bar and rod
QQ-A-200/11, 15	Extruded bar, rod, and shapes
AMS 4126	Forging
AMS 4141	Die forging
AMS 4147	Forging
MIL-A-22771	Forging
QQ-A-367	Forging

Sample problem: Find F_{tu} at 250 F following a complex exposure of 300 F, 8 hours plus 350 F, 1 hour.

1. Reduce given complex exposure by converting 350 F exposure to equivalent exposure time at 300 F.*
   a. On the 350 F single exposure temperature line find 350 F, 1 hour.
   b. From this point move vertically to the 300 F exposure temperature line and then read right, 12 hours' exposure.
   c. Total equivalent exposure time at 300 F is therefore 8 hours + 12 hours or 20 hours.

*Choice of reference temperature is optional as long as it permits computation within the bounds of the figures.

2. Find F_{tu} at 250 F following 300 F, 20 hours' exposure:
   a. On the 300 F exposure temperature line find 300 F, 20 hours.
   b. From this point move vertically to the 250 F test temperature curve and then read left, 76 percent F_{tu}.

Solution: F_{tu} is 76 percent of the original room temperature F_{tu}. F_{ty} is determined in like manner. F_{cy} can be closely estimated by using the percent reduction factor determined for F_{ty}. For specific data, see Reference 3.7.4.1.

Stressed Thermal Exposure—Stress applied during sample and complex thermal exposure of 7075-T6 can have additional effect in reducing material strength. However, the effect becomes significant only when exposure strains exceed 0.2 percent. For specific data, see Reference 3.7.4.1.

Figures 3.7.4.1.1(c) through 3.7.4.1.5(b) present elevated temperature curves for various mechanical properties. Figures 3.7.4.1.6(a) through (m) present tensile and compressive stress-strain and tangent-modulus curves at several temperatures. Figures 3.7.4.1.6(n) through (q) are full-range stress-strain curves for various products. Figures 3.7.4.1.8(a) through (h) provide room-temperature fatigue curves for T6 temper products. Fatigue-crack propagation data for sheet are presented in Figure 3.7.4.1.9. Graphical displays of the residual strength behavior of center-cracked tension panels are presented in Figure 3.7.4.1.10(a) through (h).

3.7.4.2 *T73, T7351, T7352, T73510, T73511 Tempers.*—Figures 3.7.4.2.6(a) through (d) present stress-strain and tangent-modulus curves for various products and tempers. Figures 3.7.4.2.6(e) and (f) are full-range stress-strain curves at room temperature for extrusion. Fatigue-crack-propagation data for plate are presented in Figures 3.7.4.2.9(a) through (c). Graphical displays of the residual strength behavior of center-cracked tension panels are presented in Figures 3.7.4.2.10(a) and (b).

TABLE 3.7.4.0(b$_1$). *Design Mechanical and Physical Properties of 7075 Aluminum Alloy Sheet and Plate*

Specification	AMS 4045 and QQ-A-250/12																				
Form	Sheet							Plate													
Temper	T6 and T62[a]							T651													
Thickness, in.	0.008-0.011	0.012-0.039		0.040-0.125		0.126-0.249		0.250-0.499		0.500-1.000		1.001-2.000		2.001-2.500		2.501-3.000		3.001-3.500		3.501-4.000	
Basis	S	A	B	A	B	A	B	A	B	A	B	A	B	A	B	A	B	A	B	A	B
Mechanical Properties:																					
F_{tu}, ksi:																					
L	...	76	78	78	80	78	80	77	79	77	79	76	78	75	77	71	73	70	72	66	68
LT	74	76	78	78	80	78	80	78	80	78	80	77	79	76	78	72	74	71	73	67	69
ST	...	...	...	...	...	...	...	...	...	...	...	...	...	70	71	66	68	65	67	61	63
F_{ty}, ksi:																					
L	...	69	72	70	72	71	73	69	71	70	72	69	71	66	68	63	65	60	62	56	58
LT	63	67	70	68	70	69	71	67	69	68	70	67	69	64	66	61	63	58	60	54	56
ST	...	...	...	...	...	...	...	...	...	...	...	...	...	59	61	56	58	54	55	50	52
F_{cy}, ksi:																					
L	...	68	71	69	71	70	72	67	69	68	70	66	68	62	64	58	60	55	57	51	52
LT	...	71	74	72	74	73	75	71	73	72	74	71	73	68	70	65	67	61	64	57	59
ST	...	...	...	...	...	...	...	...	...	...	...	...	...	67	70	64	66	61	63	57	59
F_{su}, ksi	...	46	47	47	48	47	48	43	44	44	45	44	45	44	45	42	43	42	43	39	41
F_{bru}[b], ksi:																					
(e/D = 1.5)	...	118	121	121	124	121	124	117	120	117	120	116	119	114	117	108	111	107	110	101	104
(e/D = 2.0)	...	152	156	156	160	156	160	145	148	145	148	143	147	141	145	134	137	132	135	124	128
F_{bry}[b], ksi:																					
(e/D = 1.5)	...	100	105	102	105	103	106	97	100	100	103	100	103	98	101	94	97	89	93	84	87
(e/D = 2.0)	...	117	122	119	122	121	124	114	118	117	120	117	120	113	117	109	112	104	108	98	103
e, percent (S-basis):																					
LT	5	7	...	8	...	8	...	9	...	7	...	6	...	5	...	5	...	5	...	3	...
E, 10^3 ksi	10.3							10.3													
E_c, 10^3 ksi	10.5							10.6													
G, 10^3 ksi	3.9							3.9													
μ	0.33							0.33													
Physical Properties:																					
ω, lb/in.^{3}	0.101																				
C, K, and α	See Figure 3.7.4.0																				

[a]Design allowables were based upon data obtained from testing T6 temper sheet and from testing samples of sheet, supplied in the O or F temper, which were heat treated to demonstrate response to heat treatment by suppliers. Properties obtained by the user may be lower than those listed if the material has been formed or otherwise cold worked, particularly in the annealed temper, prior to solution heat treatment.
[b]Bearing values are "dry pin" values per Section 1.4.7.1. See Table 3.1.2.1.1.

TABLE 3.7.4.0(b$_2$). *Design Mechanical and Physical Properties of 7075 Aluminum Alloy Plate—Continued*

Specification	AMS 4044 and QQ-A-250/12						QQ-A-250/12							
Form	Plate													
Temper	T62[a]													
Thickness, in.	0.250-0.499		0.500-1.000		1.001-2.000		2.001-2.500		2.501-3.000		3.001-3.500		3.501-4.000	
Basis	A	B	A	B	A	B	A	B	A	B	A	B	A	B
Mechanical Properties:														
F_{tu}, ksi:														
L	74	76	74	76	73	75	72	74	69	71	68	70	64	66
LT	78	80	78	80	77	79	76	78	72	74	71	73	67	69
ST	...	...	...	...	...	...	70	71	66	68	65	67	61	63
F_{ty}, ksi:														
L	65	67	66	68	64	65	60	62	56	58	52	54	48	49
LT	67	69	68	70	67	69	64	66	61	63	58	60	54	56
ST	...	...	...	...	...	...	59	61	56	58	54	55	50	52
F_{cy}, ksi:														
L	70	72	70	72	68	70	63	65	59	61	55	57	50	52
LT	70	72	71	73	68	71	65	67	61	63	57	59	52	54
ST	...	...	...	...	...	...	63	65	60	62	57	59	53	55
F_{su}, ksi	43	44	44	45	44	45	44	45	42	43	42	43	39	41
F_{bru}[b], ksi:														
(e/D = 1.5)	117	120	117	120	116	119	114	117	108	111	107	110	101	104
(e/D = 2.0)	145	148	145	148	143	147	141	145	134	137	132	135	124	128
F_{bry}[b], ksi:														
(e/D = 1.5)	97	100	100	103	100	103	98	101	94	97	89	93	84	87
(e/D = 2.0)	114	118	117	120	117	120	113	117	109	112	104	108	98	103
e, percent (S-basis):														
LT	9	...	7	...	6	...	5	...	5	...	5	...	3	...
E, 10^3 ksi	10.3													
E_c, 10^3 ksi	10.6													
G, 10^3 ksi	3.9													
μ	0.33													
Physical Properties:														
ω, lb/in.^{3}	0.101													
C, K, and α	See Figure 3.7.4.0													

[a]Design allowables were based upon data obtained from testing samples of plate, supplied in O or F temper, which were heat treated to demonstrate response to heat treatment by suppliers. Properties obtained by the user may be lower than those listed if the material has been formed or otherwise cold worked, particularly in the annealed temper, prior to solution heat treatment.

[b]Bearing values are "dry pin" values per Section 1.4.7.1. See Table 3.1.2.1.1.

TABLE 3.7.4.0(b$_3$). *Design Mechanical and Physical Properties of 7075 Aluminum Alloy Sheet and Plate—Continued*

Specification	QQ-A-250/12	AMS 4078 and QQ-A-250/12												
Form	Sheet	Plate												
Temper	T73	T7351												
Thickness, in.	0.040-0.249	0.250-0.499	0.500-1.000		1.001-1.500		1.501-2.000		2.001-2.500		2.501-3.000		3.001-3.500	3.501-4.000
Basis	S	S	A	B	A	B	A	B	A	B	A	B	S	S
Mechanical Properties:														
F_{tu}, ksi:														
L	67	68	68	70	67	69	66	68	65	67	63	65	62	60
LT	67	69	69	71	68	70	67	69	66	68	64[c]	66	63	61
ST	...	...	...	...	...	...	63	65	62	64	60	62	59	57
F_{ty}, ksi:														
L	56	57	57	59	57	59	55	57	52	55	49	53	49	48
LT	56	57	57	59	57	59	55	57	52[b]	55	49[c]	53	49	48
ST	...	...	...	...	...	...	52	54	49	52	47	50	47	46
F_{cy}, ksi:														
L	55	56	56	58	56	58	53	55	50	53	47	51	47	45
LT	58	59	59	61	59	61	57	59	54	57	51	55	51	50
ST	...	...	...	...	...	...	59	61	55	58	51	55	50	48
F_{su}, ksi	38	38	38	39	38	40	39	40	39	40	38	39	38	37
F_{bru}[a], ksi:														
(e/D = 1.5)	105	102	103	106	103	106	102	106	102	105	100	103	99	96
(e/D = 2.0)	134	131	132	136	132	136	132	136	131	135	128	132	127	124
F_{bry}[a], ksi:														
(e/D = 1.5)	84	79	81	83	83	86	82	85	79	83	76	81	76	76
(e/D = 2.0)	102	95	97	100	99	102	97	101	93	99	89	96	89	88
e, percent (S-basis):														
LT	8	7	7	...	6	...	6	...	6	...	6	...	6	6
E, 10^3 ksi	10.3	10.3												
E_c, 10^3 ksi	10.5	10.6												
G, 10^3 ksi	3.9	3.9												
μ	0.33	0.33												
Physical Properties:														
ω, lb/in.^{3}	0.101													
C, K, and α	See Figure 3.7.4.0													

[a]Bearing values are "dry pin" values per Section 1.4.7.1. See Table 3.1.2.1.1.
[b]The A value is higher than specification values as follows: F_{ty}(LT) = 53 ksi.
[c]A values are higher than specification values as follows: F_{tu}(LT) = 65 ksi and F_{ty}(LT) = 52 ksi.

TABLE 3.7.4.0(b_4). *Design Mechanical and Physical Properties of 7075 Aluminum Alloy Sheet and Plate—Continued*

Specification	QQ-A-250/24				
Form	Sheet and plate				
Temper	T76	T7651			
Thickness, in.	0.063-0.249	0.250-0.499	0.500-1.000	1.001-1.500	1.501-2.000
Basis	S	S	S	S	S
Mechanical Properties:					
F_{tu}, ksi:					
L	72	71	70	70	70
LT	73	72	71	71	71
ST	...	...	...	...	65
F_{ty}, ksi:					
L	62	60	59	59	59
LT	62	61	60	60	60
ST	...	...	...	...	56
F_{cy}, ksi:					
L	61	60	59	59	59
LT	65	64	63	63	63
ST	...	...	...	...	63
F_{su}, ksi	42	40	41	42	43
$F_{bru}{}^a$, ksi:					
(e/D = 1.5)	112	109	108	108	108
(e/D = 2.0)	145	141	140	140	140
$F_{bry}{}^a$, ksi:					
(e/D = 1.5)	88	86	86	86	87
(e/D = 2.0)	102	99	99	99	100
e, percent:					
LT	8	8	6	5	5
E, 10^3 ksi	10.3	10.3			
E_c, 10^3 ksi	10.5	10.6			
G, 10^3 ksi	3.9	3.9			
μ	0.33	0.33			
Physical Properties:					
ω, lb/in.^{3}	0.101				
C, K, and α	See Figure 3.7.4.0				

[a]Bearing values are "dry pin" values per Section 1.4.7.1. See Table 3.1.2.1.1.

TABLE 3.7.4.0(c_1). *Design Mechanical and Physical Properties of Clad 7075 Aluminum Alloy Sheet*

Specification	AMS 4049								
Form	Sheet								
Temper	T6								
Thickness, in.	0.008-0.011	0.012-0.039		0.040-0.062		0.063-0.187		0.188-0.249	
Basis	S	A	B	A	B	A	B	A	B
Mechanical Properties:									
F_{tu}, ksi:									
L	...	71	74	71	75	74	77	75	77
LT	68	71	74	71	75	74[a]	77	75	77
F_{ty}, ksi:									
L	...	62	65	63	66	66	69	66	68
LT	58	60	63	61	64	64	67	64	66
F_{cy}, ksi:									
L	...	61	64	62	65	65	68	65	67
LT	...	64	67	65	68	68	71	68	70
F_{su}, ksi	...	42	44	42	45	44	46	45	46
F_{bru}[b], ksi:									
(e/D = 1.5)	...	110	115	110	116	115	119	116	119
(e/D = 2.0)	...	142	148	142	150	148	154	150	154
F_{bry}[b], ksi:									
(e/D = 1.5)	...	90	94	91	96	96	100	96	99
(e/D = 2.0)	...	105	110	106	112	112	117	112	115
e, percent (S-basis):									
LT	5	8	...	9	...	9	...	9	...
E, 10^3 ksi:									
Primary	10.3					10.3		10.3	
Secondary	9.5					9.8		10.0	
E_c, 10^3 ksi:									
Primary	10.5					10.5		10.5	
Secondary	9.7					10.0		10.2	
G, 10^3 ksi	...					...		...	
μ	0.33					0.33		0.33	
Physical Properties:									
ω, lb/in.^{3}	0.101								
C, K, and α	...								

[a] S-basis. The A value is 75 ksi.
[b] Bearing values are "dry pin" values per Section 1.4.7.1.

TABLE 3.7.4.0(c_2). *Design Mechanical and Physical Properties of Clad 7075 Aluminum Alloy Sheet—Continued*

Specification	QQ-A-250/13								
Form	Sheet								
Temper	T6 and T62[a]								
Thickness, in.	0.008-0.011	0.012-0.039		0.040-0.062		0.063-0.187		0.188-0.249	
Basis	S	A	B	A	B	A	B	A	B
Mechanical Properties:									
F_{tu}, ksi:									
L	...	70	74	71	75	73	77	75	77
LT	68	70[c]	74	71	75	73[d]	77	75	77
F_{ty}, ksi:									
L	...	62	65	63	66	65	69	66	68
LT	58	60	63	61	64	63[e]	67	64	66
F_{cy}, ksi:									
L	...	61	64	62	65	64	68	65	67
LT	...	64	67	65	68	67	71	68	70
F_{su}, ksi	...	42	44	42	45	44	46	45	46
F_{bru}[b], ksi:									
(e/D = 1.5)	...	108	115	110	116	113	119	116	119
(e/D = 2.0)	...	140	148	142	150	146	154	150	154
F_{bry}[b], ksi:									
(e/D = 1.5)	...	90	94	91	96	94	100	96	99
(e/D = 2.0)	...	105	110	106	112	110	117	112	115
e, percent (S-basis):									
LT	5	7	...	8	...	8	...	8	...
E, 10^3 ksi:									
Primary	10.3					10.3		10.3	
Secondary	9.5					9.8		10.0	
E_c, 10^3 ksi:									
Primary	10.5					10.5		10.5	
Secondary	9.7					10.0		10.2	
G, 10^3 ksi	...					...		...	
μ	0.33					0.33		0.33	
Physical Properties:									
ω, lb/in.^{3}	0.101								
C, K, and α	...								

[a]Design allowables were based upon data obtained from testing T6 temper sheet and from testing samples of sheet, supplied in the O or F temper, which were heat treated to demonstrate response to heat treatment by suppliers. Properties obtained may be lower than those listed if the material has been formed or otherwise cold worked, particularly in the annealed temper, prior to solution heat treatment.

[b]Bearing values are "dry pin" values per Section 1.4.7.1.

[c]S-basis. The A value is 71 ksi.

[d]S-basis. The A value is 75 ksi.

[e]S-basis. The A value is 64 ksi.

TABLE 3.7.4.0(c_3). *Design Mechanical and Physical Properties of Clad 7075 Aluminum Alloy Plate—Continued*

Specification	AMS 4049 and QQ-A-250/13													
Form	Plate													
Temper	T651													
Thickness, in.	0.250-0.499		0.500-1.000[a]		1.001-2.000[a]		2.001-2.500[a]		2.501-3.000[a]		3.001-3.500[a]		3.501-4.000[a]	
Basis	A	B	A	B	A	B	A	B	A	B	A	B	A	B
Mechanical Properties:														
F_{tu}, ksi:														
L	74	76	75	77	74	76	73	75	69	71	68	70	64	66
LT	75	77	76	78	75	77	74	76	70	72	69	71	65	67
ST	...	...	...	...	...	...	70	71	66	68	65	67	61	63
F_{ty}, ksi:														
L	67	69	68	70	67	69	64	66	61	63	58	60	54	56
LT	65	67	66	68	65	67	62	64	59	61	56	58	52	54
ST	...	...	...	...	...	...	59	61	56	58	54	55	50	52
F_{cy}, ksi:														
L	65	67	66	68	64	66	60	62	57	58	53	55	49	51
LT	69	71	70	72	69	71	65	68	62	64	59	61	55	57
ST	...	...	...	...	...	...	67	70	64	66	61	63	57	59
F_{su}, ksi	42	43	42	44	42	44	43	44	41	42	40	42	38	39
F_{bru}[b], ksi:														
(e/D = 1.5)	113	116	114	117	113	116	111	114	105	108	104	107	98	101
(e/D = 2.0)	139	143	141	145	139	143	137	141	130	134	128	132	121	124
F_{bry}[b], ksi:														
(e/D = 1.5)	94	97	97	100	97	100	95	98	90	94	86	89	80	84
(e/D = 2.0)	111	114	113	116	113	117	110	113	105	109	100	104	93	97
e, percent (S-basis):														
LT	9	...	7	...	6	...	5	...	5	...	5	...	3	...
E, 10^3 ksi:														
Primary	10.3													
Secondary	10.0													
E_c, 10^3 ksi:														
Primary	10.6													
Secondary	10.3													
G, 10^3 ksi	...													
μ	0.33													
Physical Properties:														
ω, lb/in.^{3}	0.101													
C, K, and α	...													

[a]These values, except in the ST direction, have been adjusted to represent the average properties across the whole section, including the 1-1/2 percent per side nominal cladding thickness.
[b]See Table 3.1.2.1.1 Bearing values are "dry pin" values per Section 1.4.7.1.

TABLE 3.7.4.0(c_4). *Design Mechanical and Physical Properties of Clad 7075 Aluminum Alloy Plate—Continued*

Specification	QQ-A-250/13													
Form	Plate													
Temper	T62[a]													
Thickness, in.	0.250-0.499		0.500-1.000[b]		1.001-2.000[b]		2.001-2.500[b]		2.501-3.000[b]		3.001-3.500[b]		3.501-4.000[b]	
Basis	A	B	A	B	A	B	A	B	A	B	A	B	A	B
Mechanical Properties:														
F_{tu}, ksi:														
L	72	73	72	74	72	73	71	72	67	69	66	68	62	64
LT	75	77	76	78	75	77	74	76	70	72	69	71	65	67
ST	...	...	...	...	...	...	70	71	66	68	65	67	61	63
F_{ty}, ksi:														
L	63	65	64	66	62	64	58	60	54	56	50	52	46	48
LT	65	67	66	68	65	67	62	64	59	61	56	58	52	54
ST	...	...	...	...	...	...	59	61	56	58	54	55	50	52
F_{cy}, ksi:														
L	68	70	68	70	66	68	62	63	57	59	53	55	48	50
LT	68	70	69	71	66	68	62	65	59	61	55	57	50	52
ST	...	...	...	...	...	...	63	65	60	62	57	59	53	55
F_{su}, ksi	42	43	42	44	42	44	43	44	41	42	40	42	38	39
$F_{bru}{}^{c}$, ksi:														
(e/D = 1.5)	113	116	114	117	113	116	111	114	105	108	104	107	98	101
(e/D = 2.0)	139	143	141	145	139	143	137	141	130	134	128	132	121	124
$F_{bry}{}^{c}$, ksi:														
(e/D = 1.5)	94	97	97	100	97	100	95	98	90	94	86	89	80	84
(e/D = 2.0)	111	114	113	116	113	117	110	113	105	109	100	104	93	97
e, percent (S-basis):														
LT	9	...	7	...	6	...	5	...	5	...	5	...	3	...
E, 10^3 ksi:														
Primary	10.3													
Secondary	10.0													
E_c, 10^3 ksi:														
Primary	10.6													
Secondary	10.3													
G, 10^3 ksi	3.9													
μ	0.33													
Physical Properties:														
ω, lb/in.^{3}	0.101													
C, K, and α	...													

[a]Design allowables were based upon data obtained from testing samples of plate, supplied in the O or F temper, which were heat treated to demonstrate response to heat treatment by suppliers. Properties obtained may be lower than those listed if the material has been formed or otherwise cold worked, particularly in the annealed temper, prior to solution heat treatment.
[b]These values, except in the ST direction, have been adjusted to represent the average properties across the whole section.
[c]Bearing values are "dry pin" values per Section 1.4.7.1. See Table 3.1.2.1.1.

TABLE 3.7.4.0(c_5). *Design Mechanical and Physical Properties of Clad 7075 Aluminum Alloy Sheet and Plate—Continued*

Specification	QQ-A-250/25				
Form	Sheet			Plate	
Temper	T76			T7651	
Thickness, in.	0.040-0.062	0.063-0.187	0.188-0.249	0.250-0.499	0.500-1.000[a]
Basis	S	S	S	S	S
Mechanical Properties:					
F_{tu}, ksi:					
L	66	67	69	68	68
LT	67	68	70	69	68
F_{ty}, ksi:					
L	56	57	59	58	57
LT	56	57	59	58	57
F_{cy}, ksi:					
L	55	56	58	57	56
LT	59	60	62	60	59
F_{su}, ksi	41	40	40	40	40
F_{bru}[b], ksi:					
(e/D = 1.5)	103	104	107	105	103
(e/D = 2.0)	133	135	139	133	131
F_{bry}[b], ksi:					
(e/D = 1.5)	80	81	84	87	87
(e/D = 2.0)	92	94	97	104	103
e, percent:					
LT	8	8	8	8	6
E, 10^3 ksi:					
Primary	10.3		10.3	10.3	
Secondary	9.8		10.0	10.0	
E_c, 10^3 ksi:					
Primary	10.5		10.5	10.6	
Secondary	10.0		10.2	10.3	
G, 10^3 ksi	...		...	...	
μ	0.33		0.33	0.33	
Physical Properties:					
ω, lb/in.^{3}	0.101				
C, K, and α	...				

[a]These values have been adjusted to represent the average properties across the whole section, including the 1-1/2 percent per side nominal cladding thickness.
[b]Bearing values are "dry pin" values per Section 1.4.7.1.

TABLE 3.7.4.0(d). *Design Mechanical and Physical Properties of 7075 Aluminum Alloy Bar, Rod, and Shapes: Rolled, Drawn, or Cold-Finished*

Specification	AMS 4122, AMS 4123, AMS 4186, AMS 4187, and QQ-A-225/9								AMS 4124 and QQ-A-225/9	
Form	Bar, rod, and shapes: rolled, drawn, or cold-finished									
Temper	T6, T651, and T62[a]								T73[b,c] or T7351[c]	
Thickness[d], in.	≤1.000		1.001-2.000		2.001-3.000		3.001-4.000		0.375-2.000	2.001-3.000
Basis	A	B	A	B	A	B	A	B	S	S
Mechanical Properties:										
F_{tu}, ksi:										
L	77	79	77	79	77	79	77	79	68	68
LT	77	79	75	77	72	74	69	71	...	65[e]
F_{ty}, ksi:										
L	66	68	66	68	66	68	66	68	56	56
LT	66	68	66	68	63	65	60	62	...	52[e]
F_{cy}, ksi:										
L	64	66	64	66	64	66	64	66	54	54
LT	...	...	...	...	...	...	...	...	...	55[e]
F_{su}, ksi	46	47	46	47	46	47	46	47	42	40
F_{bru}, ksi:										
(e/D = 1.5)	100	103	100	103	100	103	100	103	101	101
(e/D = 2.0)	123	126	123	126	123	126	123	126	131	131
F_{bry}, ksi:										
(e/D = 1.5)	86	88	86	88	86	88	86	88	81	81
(e/D = 2.0)	92	95	92	95	92	95	92	95	100	100
e, percent (S-basis):										
L	7	...	7	...	7	...	7	...	10	10
E, 10^3 ksi	10.3									
E_c, 10^3 ksi	10.5									
G, 10^3 ksi	3.9									
μ	0.33									
Physical Properties:										
ω, lb/in.^{3}	0.101									
C, K, and α	See Figure 3.7.4.0									

[a] Design allowables were based upon data obtained from testing of T6 and T651 material and from samples of material, supplied in the O or F temper, which were heat treated to T62 temper to demonstrate response to heat treatment by suppliers.
[b] Design allowables were based upon data obtained from testing T73 and T7351 temper material and from testing samples of material, supplied in the O or F temper, which were heat treated to T73 temper to demonstrate response to heat treatment by suppliers.
[c] Bearing values are "dry pin" values per Section 1.4.7.1.
[d] For rounds (rod) maximum diameter is 4 inches; for square bar, maximum size is 3½ inches; for rectangular bar, maximum thickness is 3 inches with corresponding width of 6 inches; for rectangular bar less than 3 inches in thickness, maximum width is 10 inches.
[e] ST grain direction.

TABLE 3.7.4.0(e$_1$). *Design Mechanical and Physical Properties of 7075 Aluminum Alloy Die Forging*

Specification	AMS 4126, MIL-A-22771, and QQ-A-367							MIL-A-22771 and QQ-A-367						
Form	Die forging													
Temper	T6[b]							T652						
Thickness[e], in.	≤1.000		1.001-2.000		2.001-3.000		3.001-4.000	≤1.000		1.001-2.000		2.001-3.000		3.001-4.000
Basis	A	B	A	B	A	B	S	A	B	A	B	A	B	S
Mechanical Properties:														
F_{tu}, ksi:														
L	75	78	74	77	74	76	73	75	78	74	77	74	76	73
T[a]	71[d]	...	71[d]	...	70[d]	...	70	71[d]	...	71[d]	...	70[d]	...	70
F_{ty}, ksi:														
L	64	67	63	66	63	65	62	64	67	63	66	63	65	62
T[a]	61[d]	...	61[d]	...	60[d]	...	60	60[d]	...	60[d]	...	59[d]	...	59
F_{cy}, ksi:														
L	67	70	66	69	66	68	65	64	67	63	66	63	65	62
ST	64	68	64	67	63	66	63	65	69	65	68	64	67	64
F_{su}, ksi	43	45	43	44	42	43	42	43	45	43	44	42	43	42
F_{bru}[c], ksi:														
(e/D = 1.5)	105	109	104	108	104	106	102	105	109	104	108	104	106	102
(e/D = 2.0)	135	140	133	138	133	136	131	135	140	133	138	133	136	131
F_{bry}[c], ksi:														
(e/D = 1.5)	83	87	82	86	82	84	81	83	87	82	86	82	84	81
(e/D = 2.0)	96	100	94	99	94	97	93	96	100	94	99	94	97	93
e, percent (S-basis):														
L	7	...	7	...	7	...	7	7	...	7	...	7	...	7
T[a]	3	...	3	...	3	...	2	3	...	3	...	3	...	2
E, 10^3 ksi	10.0													
E_c, 10^3 ksi	10.4													
G, 10^3 ksi	3.8													
μ	0.33													
Physical Properties:														
ω, lb/in.^{3}	0.101													
C, K, and α	See Figure 3.7.4.0													

[a] For die forgings, T indicates any grain direction not within ±15° of being parallel to the forging flow lines. Specimens to test transverse properties should be located as close to the short transverse direction as possible.
[b] When die forgings are machined before heat treatment, the mechanical properties are applicable provided the as-forged thickness is not greater than twice the thickness at time of heat treatment.
[c] Bearing values are "dry pin" values per Section 1.4.7.1.
[d] Specification value. T tensile properties are presented on an S basis only.
[e] Thickness at the time of heat treatment.

TABLE 3.7.4.0(e_2). *Design Mechanical and Physical Properties of 7075 Aluminum Alloy Die Forging—Continued*

Specification	AMS 4141, MIL-A-22771, and QQ-A-367								AMS 4141		AMS 4147, MIL-A-22771, and QQ-A-367		
Form	Die forging												
Temper	T73[a,b]										T7352		
Thickness[c], in.	≤1.000		1.001-2.000		2.001-3.000		3.001-4.000		4.001-5.000	5.001-6.000	≤3.000		3.001-4.000
Basis	A	B	A	B	A	B	A	B	S	S	A	B	S
Mechanical Properties[d]:													
F_{tu}, ksi:													
L	66	71	66	71	66	69	64	69	62	61	66	69	64
T[e]	62[g]	...	62[g]	...	62[g]	...	61[g]	...	59	58	62[g]	...	61
F_{ty}, ksi:													
L	56	61	56	59	56	59	55	59	53	51	56	59	53
T[e]	53[g]	...	53[g]	...	53[g]	...	52[g]	...	51	50	51[g]	...	49
F_{cy}, ksi:													
L	58	63	58	61	58	61	57	61	...	...	56	59	53
T[e]	55	60	55	59	55	59	54	58	...	...	55	60	53
F_{su}, ksi	39	42	39	42	39	41	38	41	...	...	39	41	38
F_{bru}[f], ksi:													
(e/D = 1.5)	96	103	96	103	96	100	93	100	...	...	96	100	93
(e/D = 2.0)	125	135	125	135	125	131	122	131	...	...	125	131	122
F_{bry}[f], ksi:													
(e/D = 1.5)	78	85	78	83	78	83	77	83	...	...	78	83	74
(e/D = 2.0)	90	98	90	94	90	94	88	94	...	...	90	94	85
e, percent (S-basis):													
L	7	...	7	...	7	...	7	...	7	6	7	...	7
T[e]	3	...	3	...	3	...	2	...	2	2	3	...	2
E, 10^3 ksi	10.0												
E_c, 10^3 ksi	10.4												
G, 10^3 ksi	3.8												
μ	0.33												
Physical Properties:													
ω, lb/in.^{3}	0.101												
C, K, and α	See Figure 3.7.4.0												

[a]When die forgings are machined before heat treatment, the mechanical properties are applicable, provided the as-forged thickness is not greater than twice the thickness at the time of heat treatment.
[b]Design allowables were based upon data obtained from testing die forgings, heat treated by suppliers, and supplied in T73 temper.
[c]Thickness at the time of heat treatment.
[d]Most of the A tensile values are higher than specification values; consequently, the A values shown are specification values.
[e]For die forgings, T indicates any grain direction not within ±15° of being parallel to the forging flow lines. Specimens to test transverse properties should be located as close to the short transverse direction as possible.
[f]Bearing values are "dry pin" values per Section 1.4.7.1.
[g]Specification value. T tensile properties are presented on an S basis only.

TABLE 3.7.4.0(f_1). *Design Mechanical and Physical Properties of 7075 Aluminum Alloy Hand Forging*

Specification	AMS 4126, MIL-A-22771, and QQ-A-367					MIL-A-22771 and QQ-A-367				
Form	Hand forging									
Temper	T6[a]					T652				
Thickness, in.	≤2.000	2.001-3.000	3.001-4.000	4.001-5.000	5.001-6.000	≤2.000	2.001-3.000	3.001-4.000	4.001-5.000	5.001-6.000
Basis	S	S	S	S	S	S	S	S	S	S
Mechanical Properties:										
F_{tu}, ksi:										
L	74	73	71	69	68	74	73	71	69	68
LT	73	71	70	68	66	73	71	70	68	66
ST	...	69	68	66	65	...	69	68	66	65
F_{ty}, ksi:										
L	63	61	60	58	56	63	61	60	58	56
LT	61	59	58	56	55	61	59	58	56	55
ST	...	58	57	56	55	...	57	56	55	54
F_{cy}, ksi:										
L	63	61	...	...	...	63	61	...	...	...
LT	61	59	...	...	...	61	59	...	...	...
ST	...	...	...	...	...	...	...	...	...	...
F_{su}, ksi	44	44	43	41	41	44	44	43	41	41
F_{bru}[b], ksi:										
(e/D = 1.5)	...	...	...	...	...	...	...	...	...	...
(e/D = 2.0)	...	...	...	...	...	...	...	...	...	...
F_{bry}[b], ksi:										
(e/D = 1.5)	...	...	...	...	...	...	...	...	...	...
(e/D = 2.0)	...	...	...	...	...	...	...	...	...	...
e, percent:										
L	9	9	8	7	6	9	9	8	7	6
LT	4	4	3	3	3	4	4	3	3	3
ST	...	3	2	2	2	...	2	1	1	1
E, 10^3 ksi	10.0									
E_c, 10^3 ksi	10.4									
G, 10^3 ksi	3.8									
μ	0.33									
Physical Properties:										
ω, lb/in.^{3}	0.101									
C, K, and α	See Figure 3.7.4.0									

[a]When hand forgings are machined before heat treatment, the section thickness at time of heat treatment shall determine the minimum mechanical properties as long as the original (as-forged) thickness does not exceed the maximum thickness of the alloy as shown in the table. The maximum cross-sectional area of hand forgings is 256 sq in.
[b]Bearing values are "dry pin" values per Section 1.4.7.1.

TABLE 3.7.4.0(f_2). *Design Mechanical and Physical Properties of 7075 Aluminum Alloy Hand Forging—Continued*

Specification	MIL-A-22771 and QQ-A-367					AMS 4147, MIL-A-22771, and QQ-A-367					
Form	Hand forging										
Temper	T73[a]					T7352					
Thickness, in.	≤2.000	2.001-3.000	3.001-4.000	4.001-5.000	5.001-6.000	≤2.000	2.001-3.000	3.001-4.000		4.001-5.000	5.001-6.000
Basis	S	S	S	S	S	S	S	A	B	S	S
Mechanical Properties:											
F_{tu}, ksi:											
L	66	66	64	62	61	66	66	64	67	62	61
LT	64	64	63	61	59	64	64	63	66	61	59
ST	...	61	60	58	57	...	61	60	63	58	57
F_{ty}, ksi:											
L	56	56	55	53	51	54	54	53	55	51	49
LT	54	54	53	51	50	52	52	50	53	48	46
ST	...	52	51	50	49	...	50	48	51	46	44
F_{cy}, ksi:											
L	56	56	...	...	...	55	55	52	55	49	46
LT	52	52	...	...	...	55	55	52	55	49	46
ST	...	...	...	...	...	55	55	53	56	51	49
F_{su}, ksi:											
L	39	39	...	...	...	39	39	38	40	37	36
LT	...	...	...	...	...	36	36	37	38	36	35
ST	...	...	...	...	...	38	38	37	39	36	35
$F_{bru}{}^{b}$, ksi:											
(e/D = 1.5)	...	...	...	...	...	86	88	89	93	86	84
(e/D = 2.0)	...	...	...	...	...	120	120	118	123	114	110
$F_{bry}{}^{b}$, ksi:											
(e/D = 1.5)	...	...	...	...	...	71	73	73	77	71	68
(e/D = 2.0)	...	...	...	...	...	90	90	87	92	83	80
e, percent (S-basis):											
L	7	7	7	7	6	7	7	7	...	7	6
LT	4	4	3	3	3	4	4	3	...	3	3
ST	...	3	2	2	2	...	3	2	...	2	2
E, 10^3 ksi	10.2										
E_c, 10^3 ksi	10.4										
G, 10^3 ksi	3.8										
μ	0.33										
Physical Properties:											
ω, lb/in.^{3}	0.101										
C, K, and α	See Figure 3.7.4.0										

[a] When hand forgings are machined before heat treatment, the section thickness at time of heat treatment shall determine the minimum mechanical properties as long as the original (as-forged) thickness does not exceed the maximum thickness for the alloy as shown in the table. The maximum cross-sectional area of hand forgings is 256 sq. in.
[b] Bearing values are "dry pin" values per Section 1.4.7.1.

TABLE 3.7.4.0(g_1). *Design Mechanical and Physical Properties of 7075 Aluminum Alloy Extrusion*

Specification	QQ-A-200/11														
Form	Extrusion (rod, bar, and shapes)														
Temper	T6, T6510, T6511, and T62[a]														
Cross-sectional area, in.^{2}	≤20												>20, ≤32	≤32	
Thickness, in.[b]	≤0.249		0.250-0.499		0.500-0.749		0.750-1.499		1.500-2.999		3.000-4.499			4.500-5.000	
Basis	A	B	A	B	A	B	A	B	A	B	A	B	S	A	B
Mechanical Properties:															
F_{tu}, ksi:															
L	78	82	81	85	81	85	81	85	81	85	81	84	78	78	81
LT	75	79	78	82	77	81	75	79	71	75	67	69	64	63	65
ST	...	...	...	...	...	...	...	...	67	71	67	69	64	63	65
F_{ty}, ksi:															
L	70	74	73	77	72	76	72	76	72	76	71	74	70	68	71
LT	66	70	69	72	67	71	65	69	61	65	56	59	55	52	55
ST	...	...	...	...	...	...	...	...	56	59	55	58	55	52	55
F_{cy}, ksi:															
L	70	74	73	77	72	76	72	76	72	76	71	74	70	68	71
LT	72	76	74	78	73	77	71	75	67	71	62	64	61	57	60
ST	...	...	...	...	...	...	...	...	62	66	62	64	61	57	60
F_{su}, ksi	41	44	43	45	43	45	43	45	42	44	40	42	39	38	40
F_{bru}[c], ksi:															
(e/D = 1.5)	111	117	115	121	115	120	113	119	110	115	106	110	102	101	105
(e/D = 2.0)	140	148	146	153	145	152	144	151	141	148	137	142	132	131	136
F_{bry}[c], ksi:															
(e/D = 1.5)	92	97	96	101	94	99	93	98	89	94	84	88	83	79	83
(e/D = 2.0)	108	114	113	119	111	117	110	116	106	112	101	105	100	95	100
e, percent (S-basis):															
L	7	...	7	...	7	...	7	...	7	...	7	...	6	6	...
E, 10^3 ksi	10.4														
E_c, 10^3 ksi	10.7														
G, 10^3 ksi	4.0														
μ	0.33														
Physical Properties:															
ω, lb/in.^{3}	0.101														
C, K, and α	See Figure 3.7.4.0														

[a]Design allowables were based upon data obtained from testing T6, T6510, and T6511 temper extrusions and from testing samples of extrusion supplied in the O or F temper, which were heat treated to T62 temper to demonstrate response to heat treatment by suppliers. Properties obtained by the user may be lower than those listed if the material has been formed or otherwise cold worked, particularly in the annealed temper, prior to solution heat treatment.
[b]For extrusions with outstanding legs, the load-carrying ability of such legs shall be determined on the basis of the properties in the appropriate column to the leg thickness.
[c]Bearing values are "dry pin" values per Section 1.4.7.1.

TABLE 3.7.4.0(g_2). *Design Mechanical and Physical Properties of 7075 Aluminum Alloy Extrusion—Continued*

Specification	QQ-A-200/11													
Form	Extrusion (rod, bars, and shapes)													
Temper	T73[a], T73510, T73511													
Cross-sectional area, in.^{2}	≤20		≤25								≤20		>20, ≤32	
Thickness, in.[b]	0.062-0.249		0.250-0.499		0.500-0.749		0.750-1.499		1.500-2.999		3.000-4.499		3.000-4.499	
Basis	A	B	A	B	A	B	A	B	A	B	A	B	A	B
Mechanical Properties:														
F_{tu}, ksi:														
L	68[c]	72	70[c]	74	70[c]	73	70[c]	73	69[c]	74	68[c]	71	65[c]	70
LT	66	70	68	72	67	70	66	69	62	67	58	61	56	60
F_{ty}, ksi:														
L	58	61	60	63	60	63	60	63	59[c]	65	57[c]	62	55[c]	60
LT	56	59	57	60	57	60	56	58	51	56	46	50	44	48
F_{cy}, ksi:														
L	58	61	60	63	60	63	60	63	59	65	57	62	55	60
LT	59	62	60	63	60	63	58	61	54	59	49	53	47	51
F_{su}, ksi	37	39	38	40	38	39	38	39	37	40	37	38	35	38
F_{bru}[d], ksi:														
(e/D = 1.5)	101	107	104	110	103	108	103	107	99	106	95	99	91	98
(e/D = 2.0)	129	137	133	141	133	139	132	138	128	138	124	130	119	128
F_{bry}[d], ksi:														
(e/D = 1.5)	82	86	84	89	84	88	83	87	79	87	72	79	70	76
(e/D = 2.0)	97	102	100	105	100	105	98	103	93	103	86	94	83	91
e, percent (S-basis):														
L	7	...	8	...	8	...	8	...	8	...	7	...	7	...
E, 10^3 ksi	10.4													
E_c, 10^3 ksi	10.7													
G, 10^3 ksi	4.0													
μ	0.33													
Physical Properties:														
ω, lb/in.^{3}	0.101													
C, K, and α	See Figure 3.7.4.0													

[a] Design allowables were based upon data obtained from testing T7351X temper extrusions and from testing samples of extrusions supplied in the O or F temper, which were heat treated to T73 temper to demonstrate response to treatment by suppliers. Properties obtained by the user may be lower than those listed if the material has been formed or otherwise cold worked, particularly in the annealed temper.
[b] For extrusions with outstanding legs, the load-carrying ability of such legs shall be determined on the basis of the properties in the appropriate column corresponding to the leg thickness.
[c] S-basis. See Table 3.7.4.0(g_3).
[d] Bearing values are "dry pin" values per Section 1.4.7.1.

TABLE 3.7.4.0(g_3). *A Values for Tensile Yield and Ultimate Strength for 7075-T73, T73510, and T73511 Extrusion*

Cross-sectional area, in.^{2} ...	≤20	≤25		≤20	>20, ≤32
Thickness, inch	0.062-0.249	0.250-1.499	1.500-2.999	3.000-4.499	3.000-4.499
Mechanical Properties:					
F_{tu}, ksi:					
L	69	71	72	69	68
F_{ty}, ksi:					
L	...	...	62	59	57

TABLE 3.7.4.0(g_4). *Design Mechanical and Physical Properties of 7075 Aluminum Alloy Extrusion—Continued*

Specification	QQ-A-200/15						
Form	Extrusion (rod, bar, and shapes)						
Temper	T76, T76510, T76511						
Cross-sectional area, in.²	≤20						
Thickness, in.[a]	0.062-0.249		0.250-0.499	0.500-0.749		0.750-1.000	
Basis	A	B	S	A	B	A	B
Mechanical Properties:							
F_{tu}, ksi:							
L	71	74	75	75	76	75	76
LT	68	71	72	71	73	70	71
F_{ty}, ksi:							
L	61	65	65	65	67	65	67
LT	57	61	61	60	62	59	61
F_{cy}, ksi:							
L	61	65	65	65	67	65	67
LT	62	66	66	65	67	64	66
F_{su}, ksi	38	40	41	41	42	40	41
F_{bru}[b], ksi:							
(e/D = 1.5)	103	107	109	109	110	109	110
(e/D = 2.0)	131	137	139	139	141	139	141
F_{bry}[b], ksi:							
(e/D = 1.5)	82	88	88	88	90	88	90
(e/D = 2.0)	98	104	104	104	107	104	107
e, percent (S-basis):							
L	7	...	7	7	...	7	...
E, 10^3 ksi	10.4						
E_c, 10^3 ksi	10.7						
G, 10^3 ksi	4.0						
μ	0.33						
Physical Properties:							
ω, lb/in.³	0.101						
C, K, and α	See Figure 3.7.4.0						

[a] For extrusions with outstanding legs, the load-carrying ability of such legs shall be determined on the basis of the properties in the appropriate column corresponding to the leg thickness.
[b] Bearing values are "dry pin" values per Section 1.4.7.1.

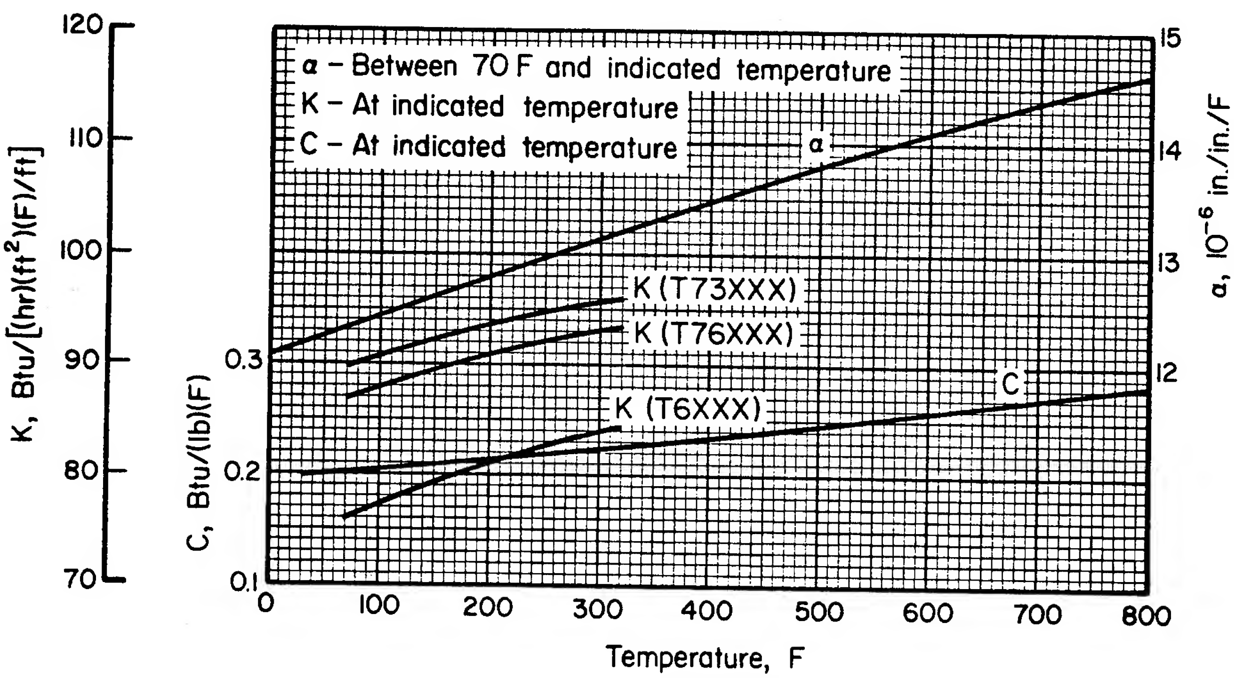

FIGURE 3.7.4.0. *Effect of temperature on the physical properties of 7075 aluminum alloy.*

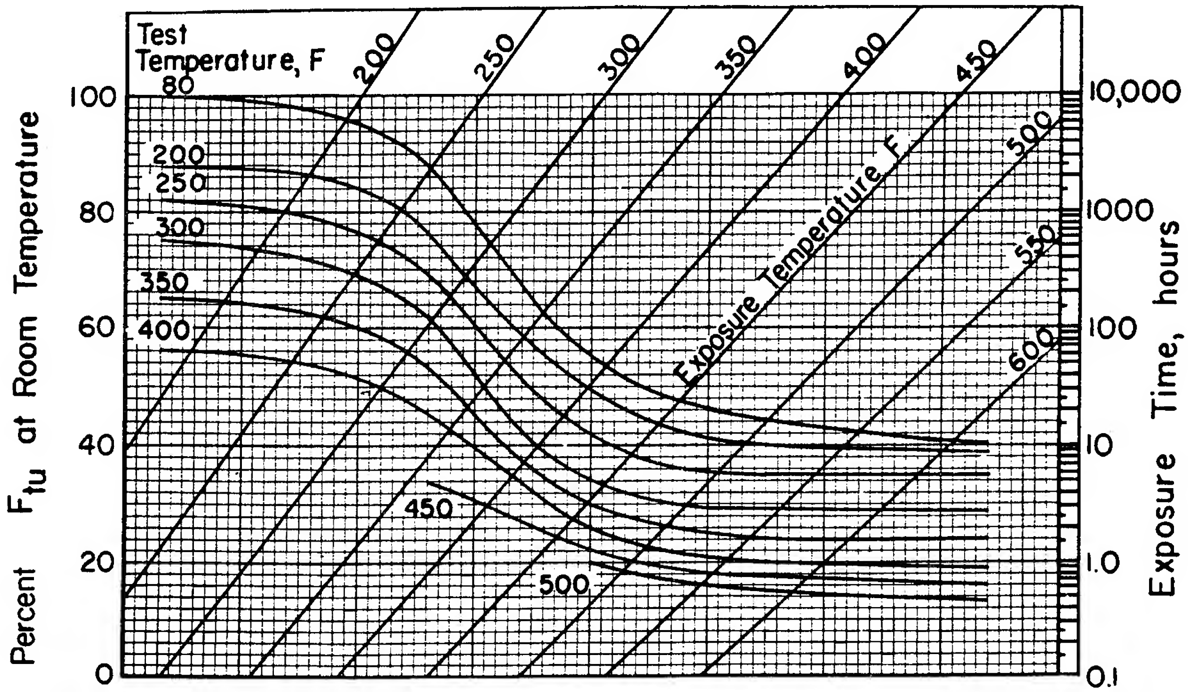

FIGURE 3.7.4.1.1(a). *Effect of temperature on the ultimate tensile strength (F_{tu}) of 7075-T6, T651, T6510, and T6511 aluminum alloy (all products). Note: Instructions for use of these curves are presented in Section 3.7.4.1.*

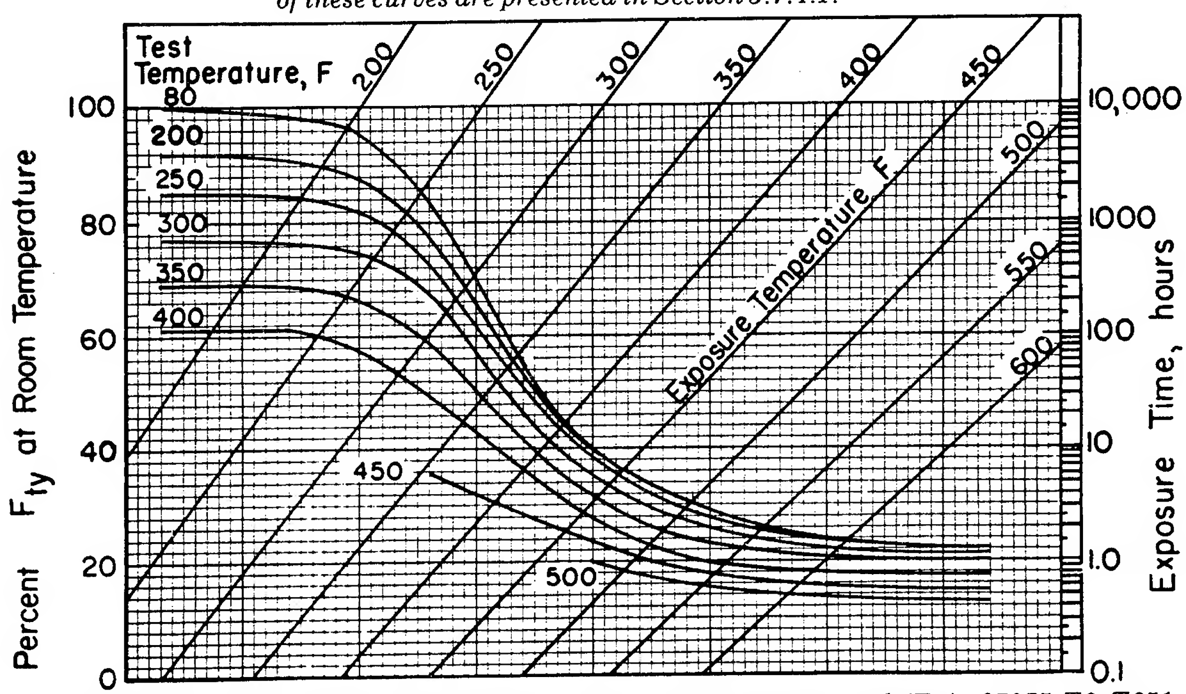

FIGURE 3.7.4.1.1(b). *Effect of temperature on the tensile yield strength (F_{ty}) of 7075-T6, T651, T6510, and T6511 aluminum alloy (all products). Note: Instructions for use of these curves are presented in Section 3.7.4.1.*

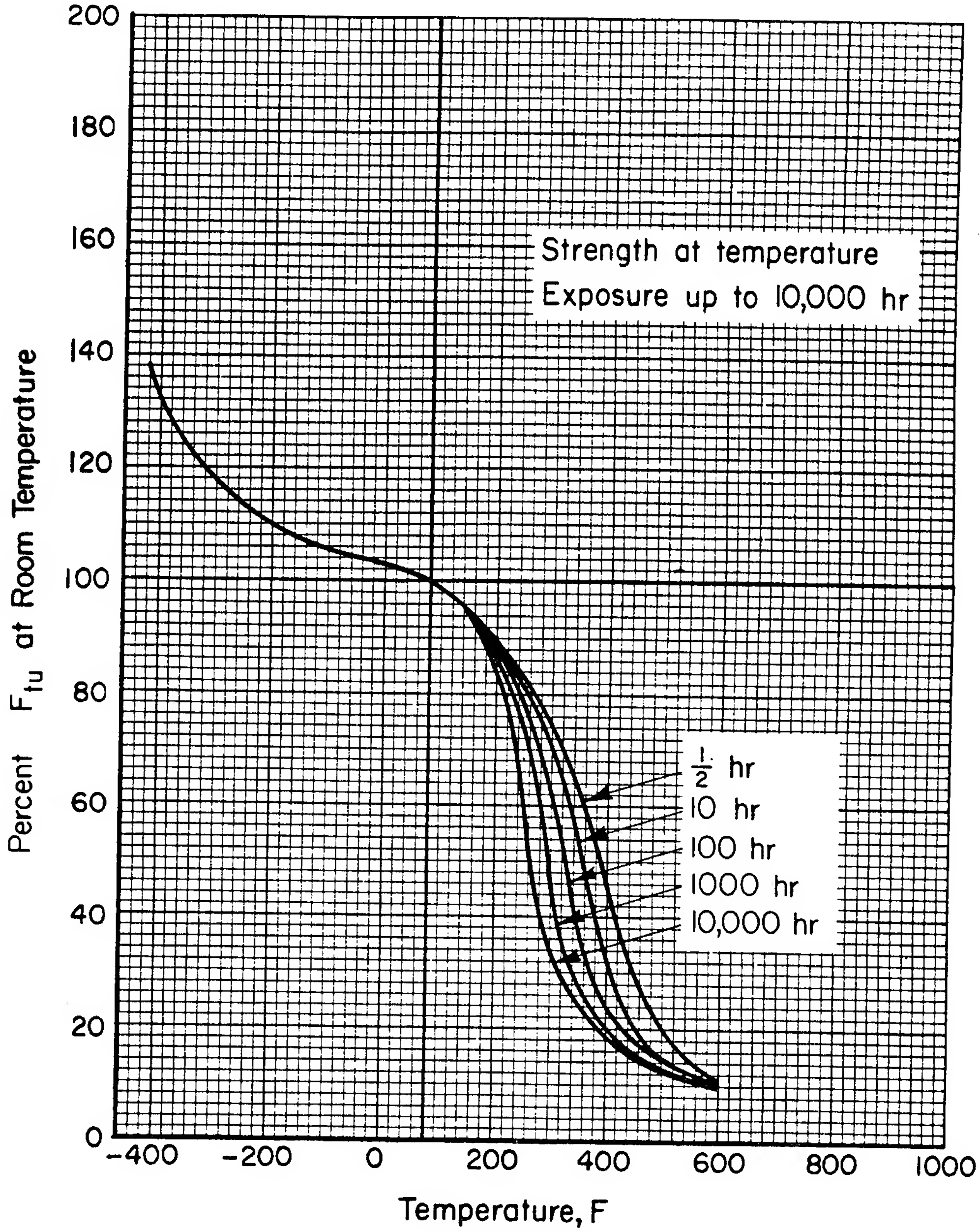

FIGURE 3.7.4.1.1(c). *Effect of temperature on the ultimate tensile strength (F_{tu}) of 7075-T6, T651, T6510, and T6511 aluminum alloy (all products).*

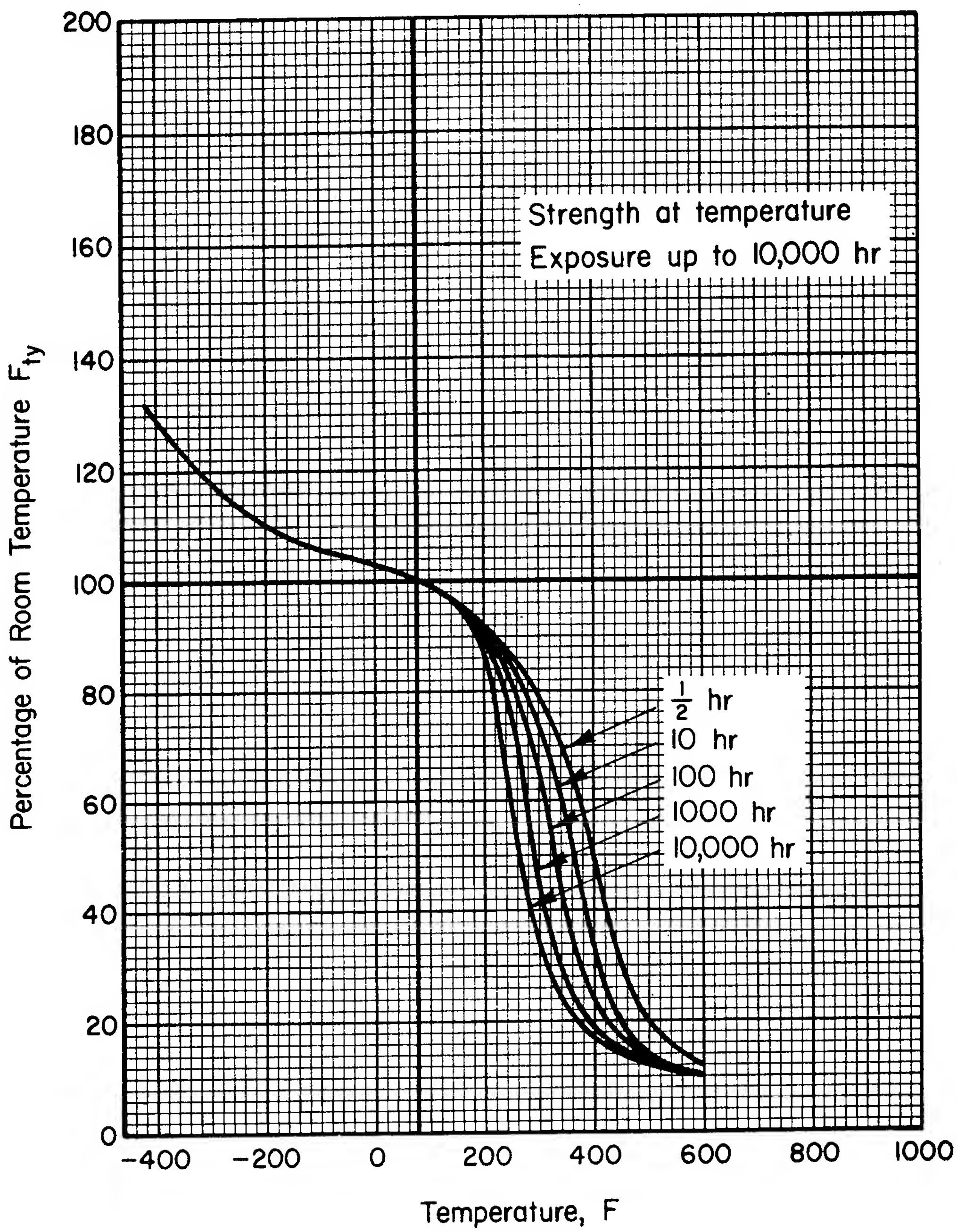

FIGURE 3.7.4.1.1(d). *Effect of temperature on the tensile yield strength (F_{ty}) of 7075-T6, T651, T6510, and T6511 aluminum alloy (all products).*

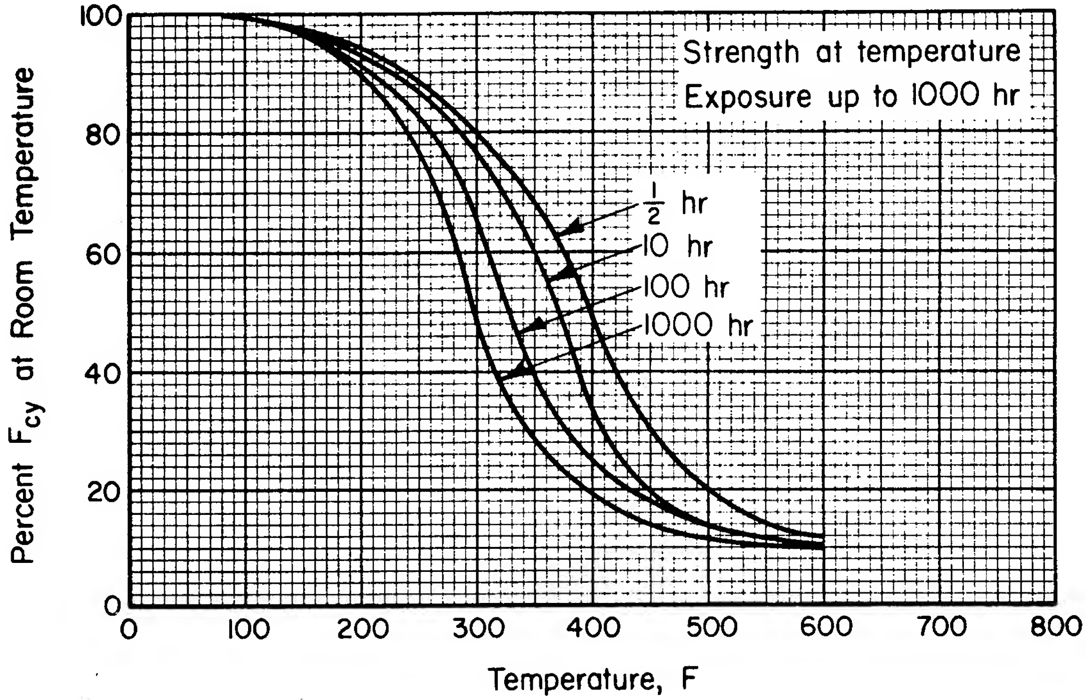

FIGURE 3.7.4.1.2(a). *Effect of temperature on the compressive yield strength (F_{cy}) of 7075-T6, T651, T6510, and T6511 aluminum alloy (all products).*

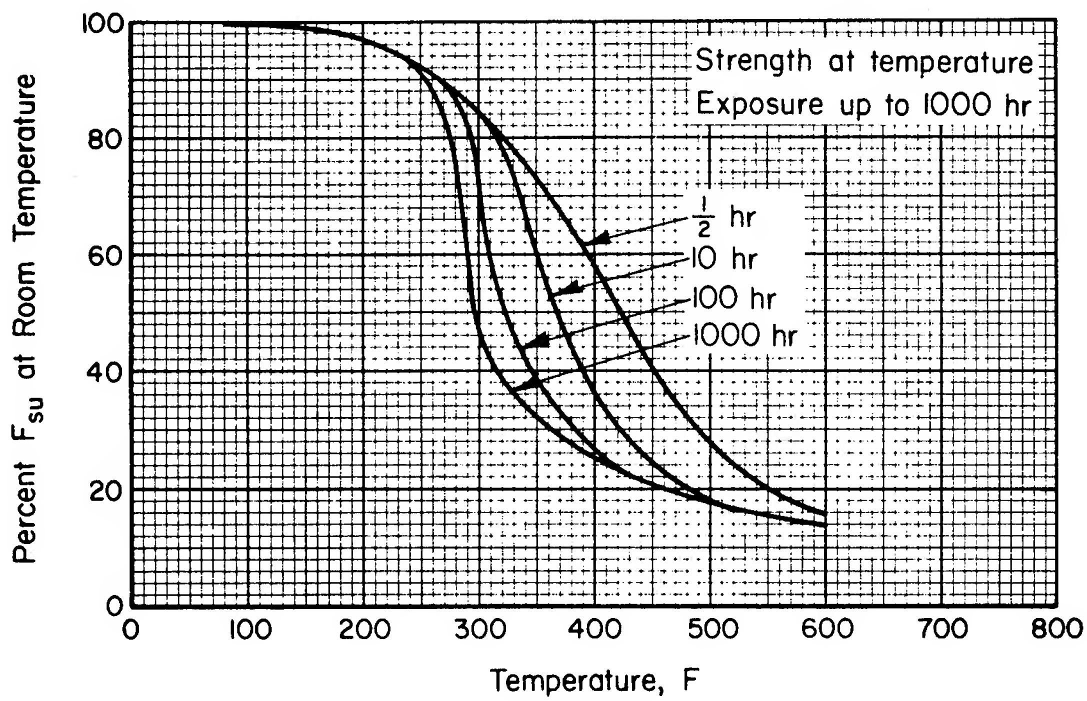

FIGURE 3.7.4.1.2(b). *Effect of temperature on the ultimate shear strength (F_{su}) of 7075-T6, T651, T6510, and T6511 aluminum alloy (all products).*

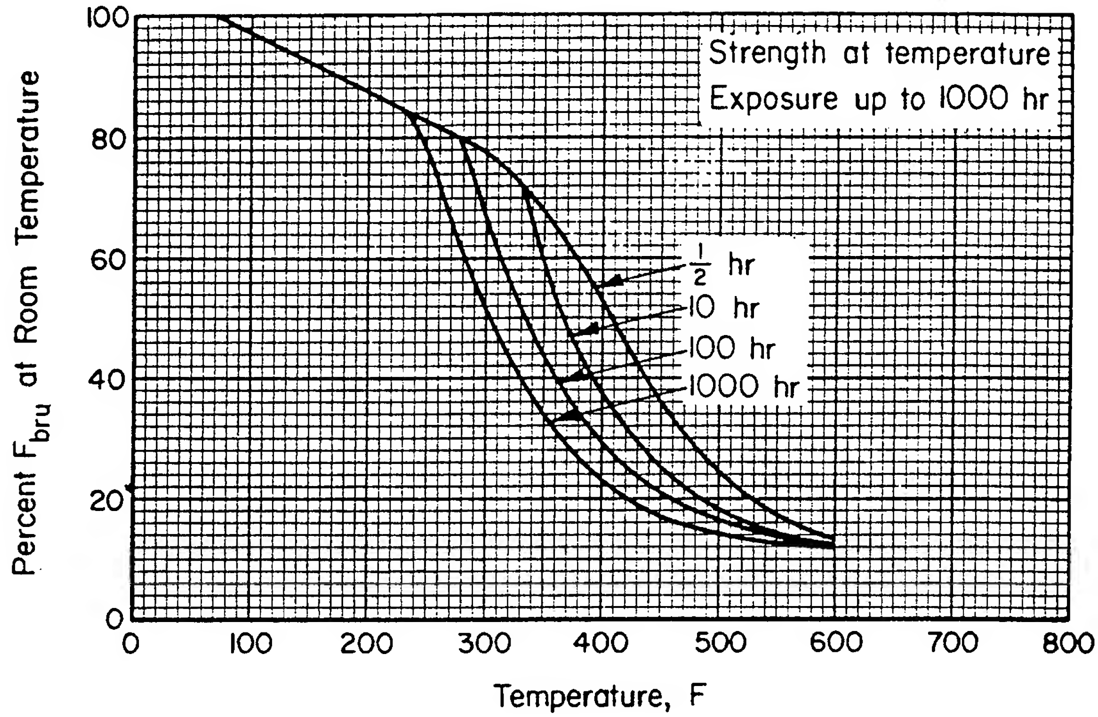

FIGURE 3.7.4.1.3(a). *Effect of temperature on the ultimate bearing strength (F_{bru}) of 7075-T6, T651, T6510, and T6511 aluminum alloy (all products).*

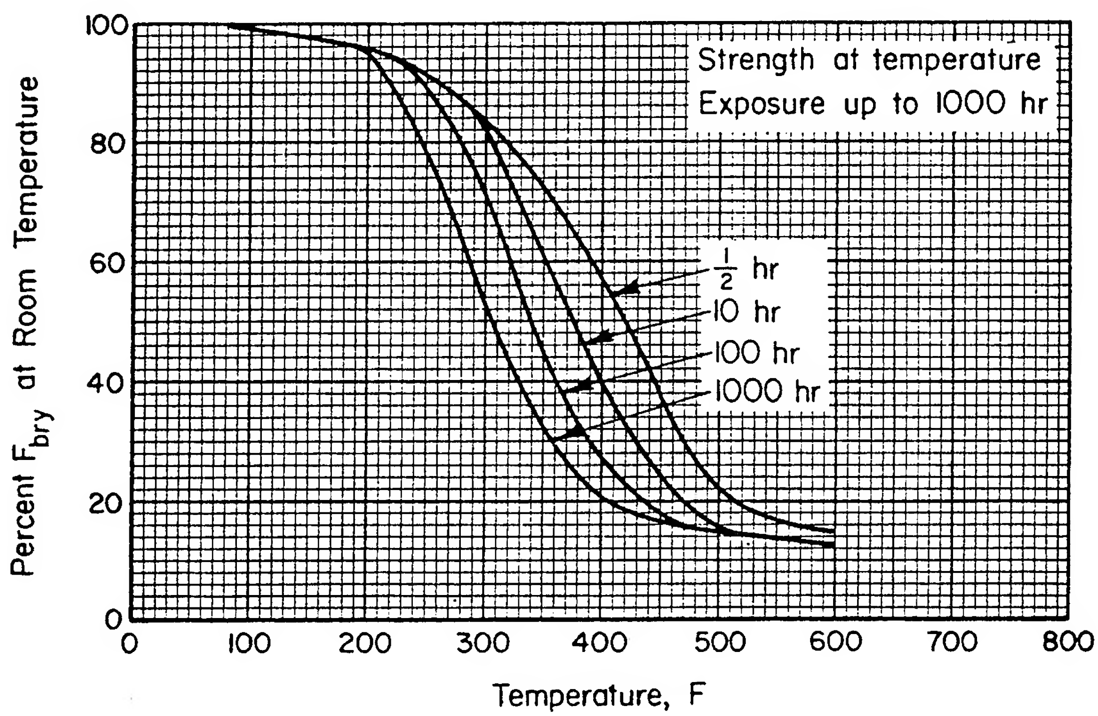

FIGURE 3.7.4.1.3(b). *Effect of temperature on the bearing yield strength (F_{bry}) of 7075-T6, T651, T6510, and T6511 aluminum alloy (all products).*

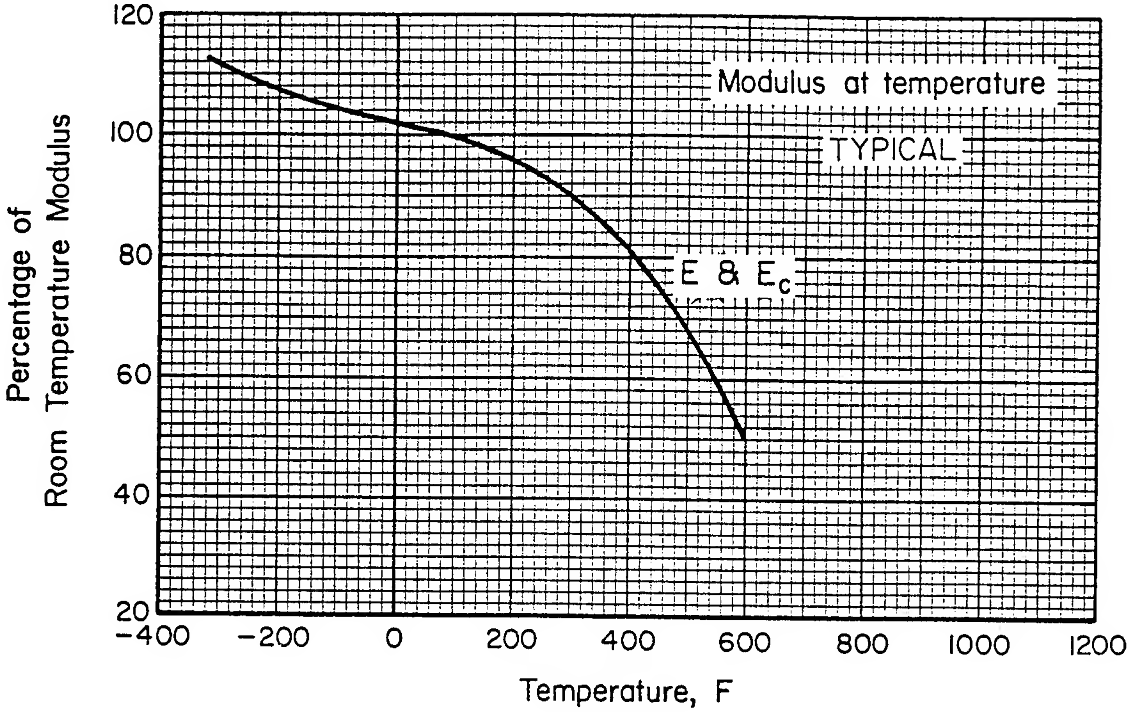

FIGURE 3.7.4.1.4. *Effect of temperature on the tensile and compressive moduli (E and E_c) of 7075 aluminum alloy.*

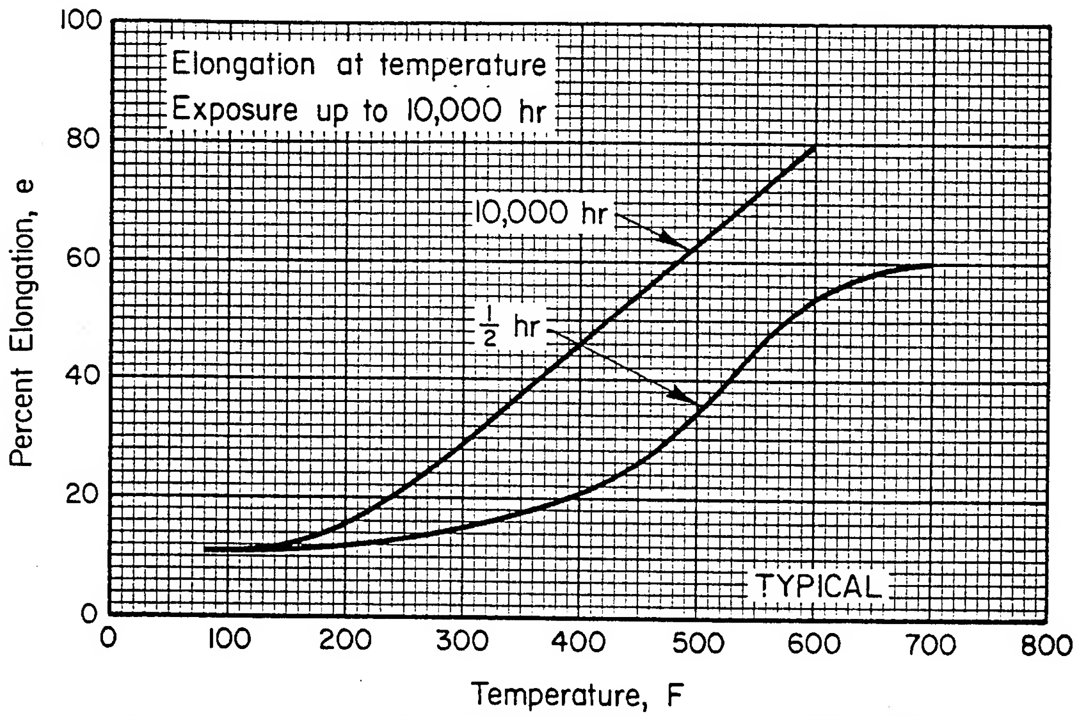

FIGURE 3.7.4.1.5(a). *Effect of temperature on the elongation of 7075-T6, T651, T6510, and T6511 aluminum alloy (all products except thick extrusions).*

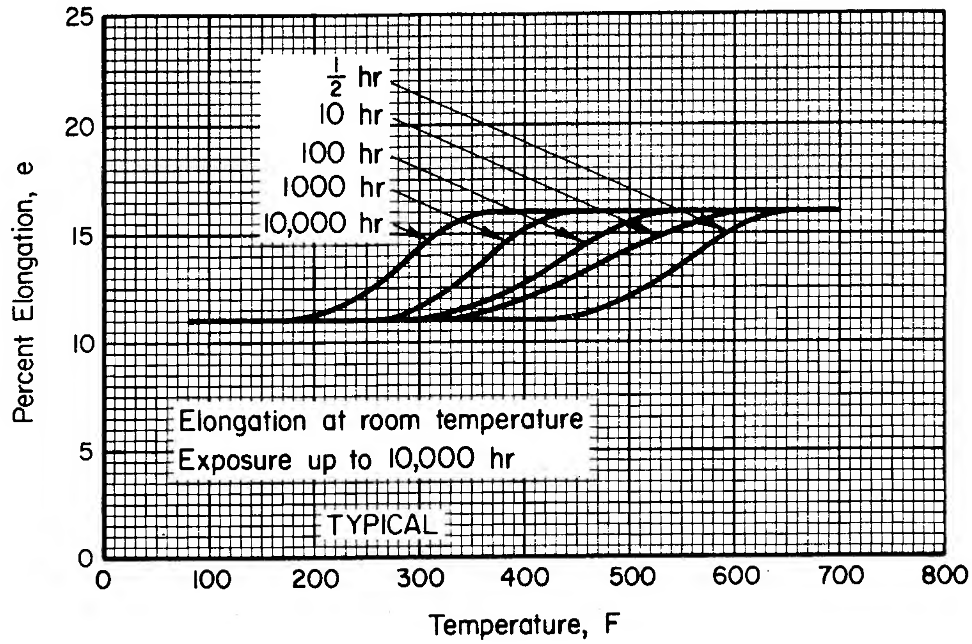

FIGURE 3.7.4.1.5(b). *Effect of exposure at elevated temperatures on the elongation of 7075-T6, T651, T6510, and T6511 aluminum alloy (all products except thick extrusions).*

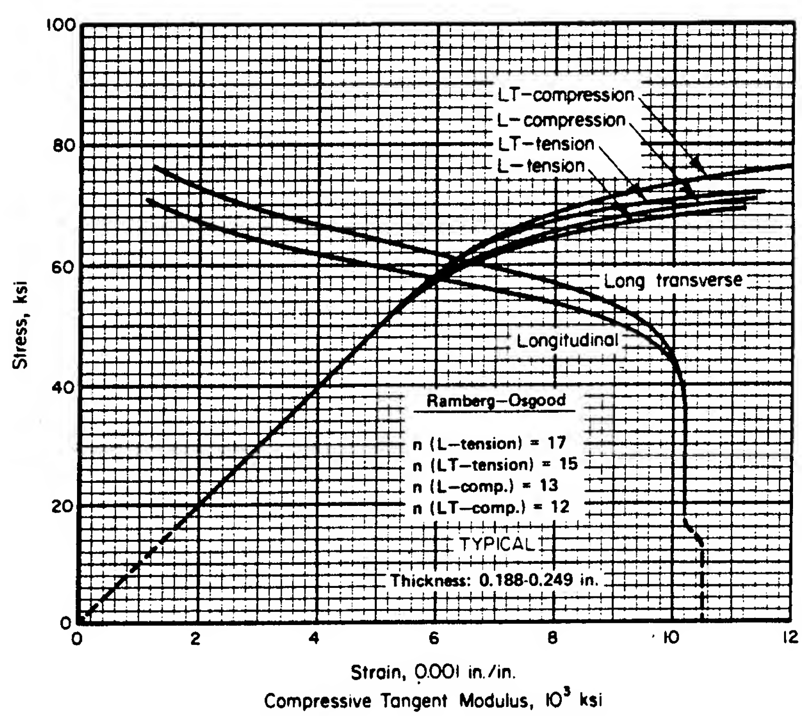

FIGURE 3.7.4.1.6(a). *Typical tensile and compressive stress-strain and compressive tangent-modulus curves for clad 7075-T6 aluminum alloy sheet at room temperature.*

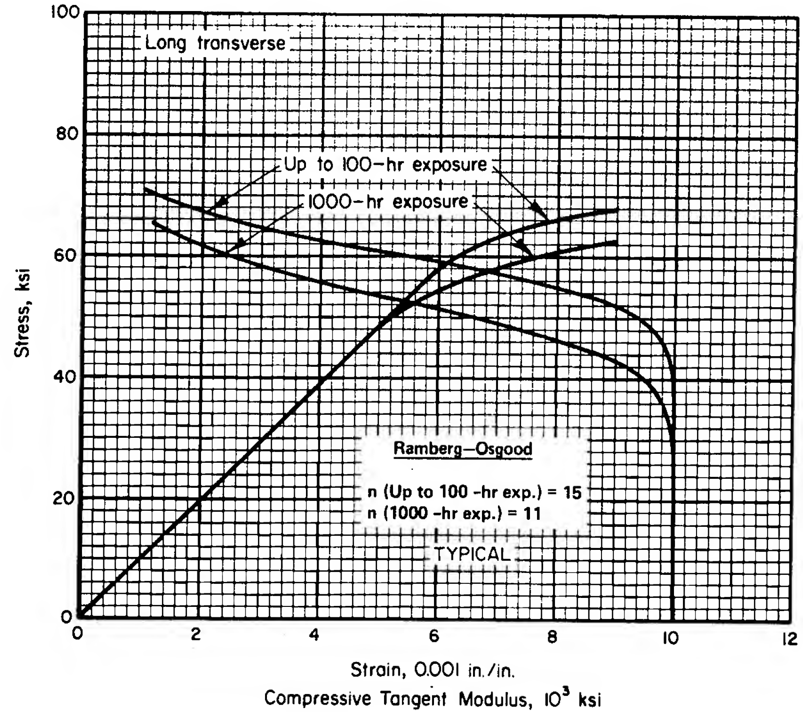

FIGURE 3.7.4.1.6(b). *Typical compressive stress-strain and compressive tangent-modulus curves for clad 7075-T6 aluminum alloy sheet at 200 F.*

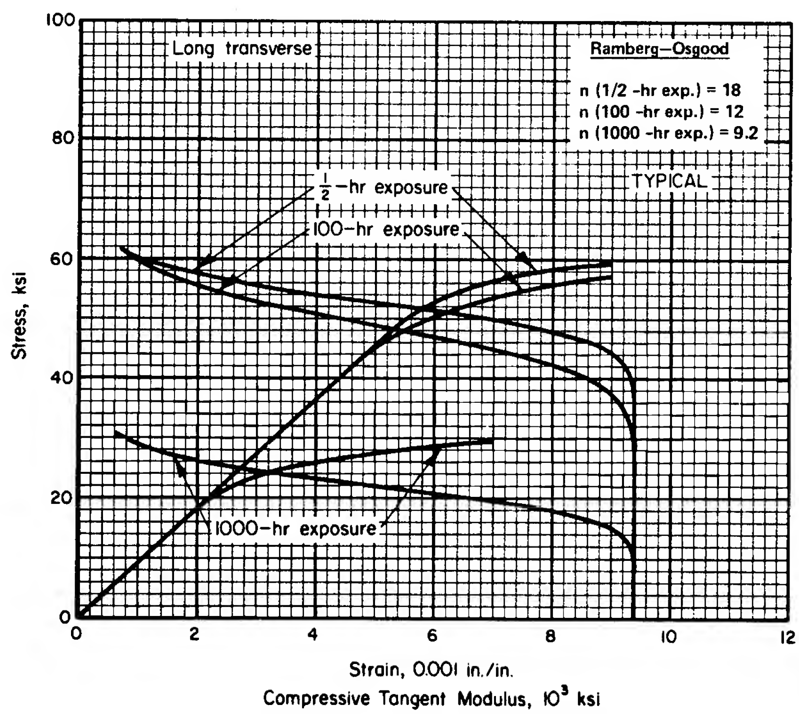

FIGURE 3.7.4.1.6(c). *Typical compressive stress-strain and compressive tangent-modulus curves for clad 7075-T6 aluminum alloy sheet at 300 F.*

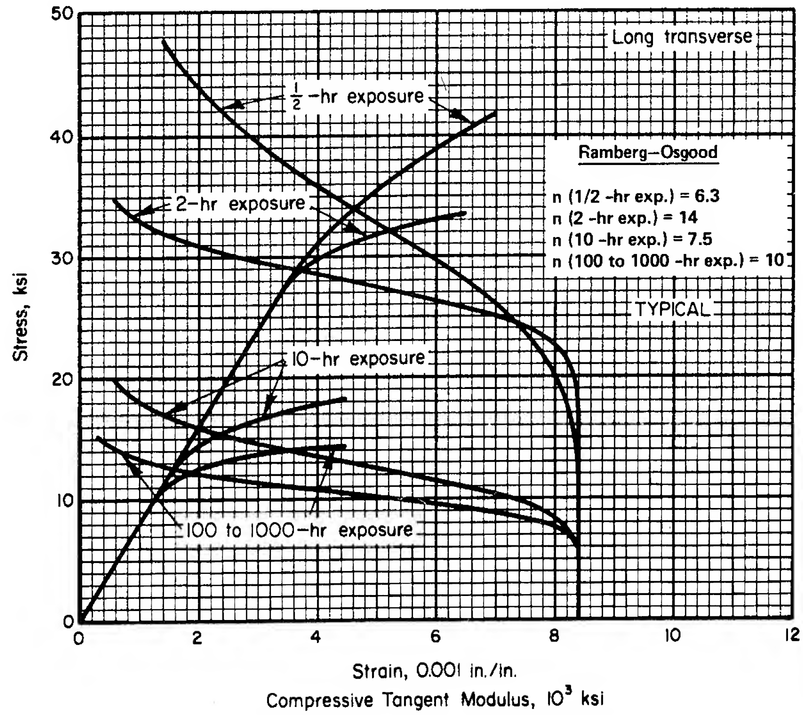

FIGURE 3.7.4.1.6(d). *Typical compressive stress-strain and compressive tangent-modulus curves for clad 7075-T6 aluminum alloy sheet at 400 F.*

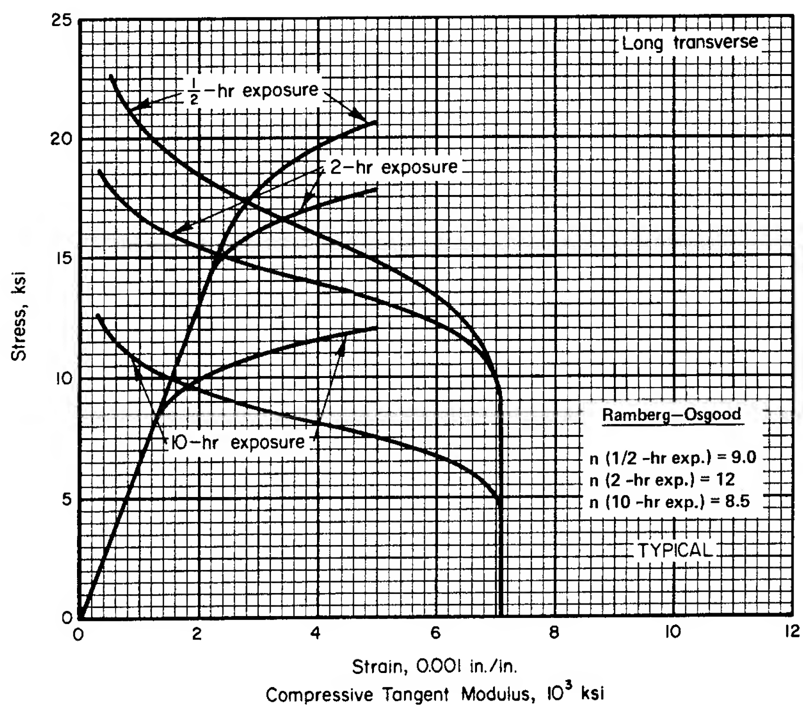

FIGURE 3.7.4.1.6(e). *Typical compressive stress-strain and compressive tangent-modulus curves for clad 7075-T6 aluminum alloy sheet at 500 F.*

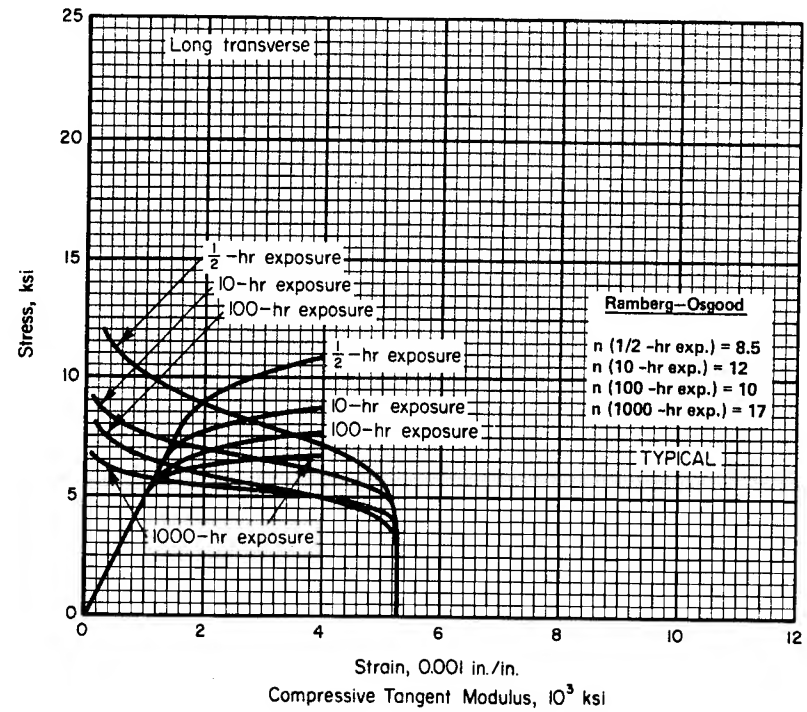

FIGURE 3.7.4.1.6(f). *Typical compressive stress-strain and compressive tangent modulus curves for clad 7075-T6 aluminum alloy sheet at 600 F.*

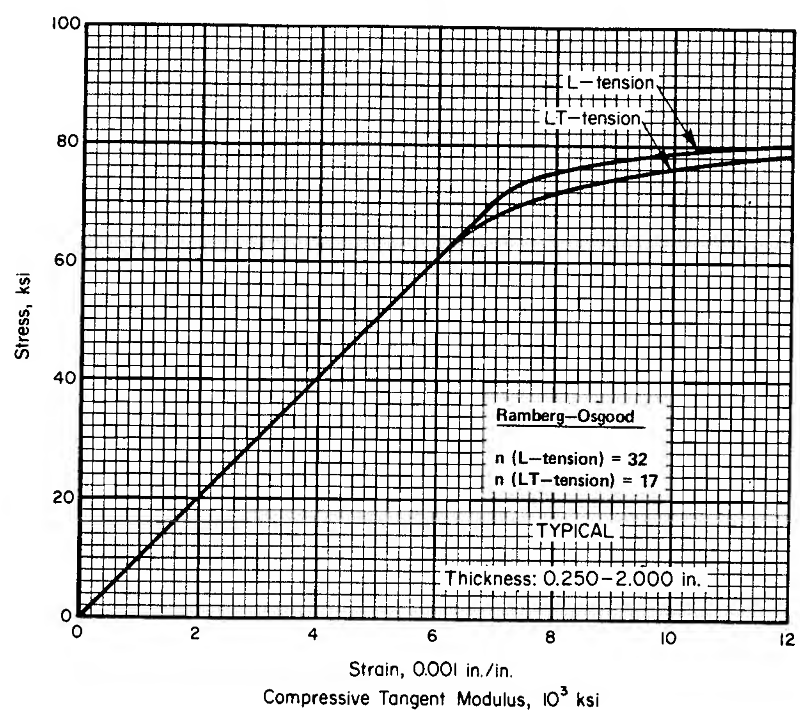

FIGURE 3.7.4.1.6(g). *Typical tensile stress-strain curves for 7075-T651 aluminum alloy plate at room temperature.*

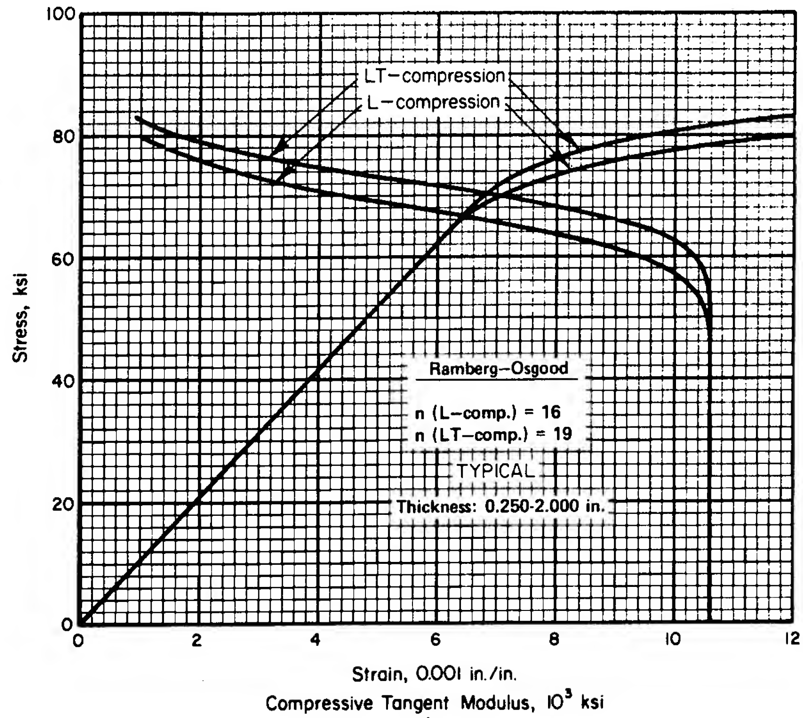

FIGURE 3.7.4.1.6(h). *Typical compressive stress-strain and compressive tangent-modulus curves for 7075-T651 aluminum alloy plate at room temperature.*

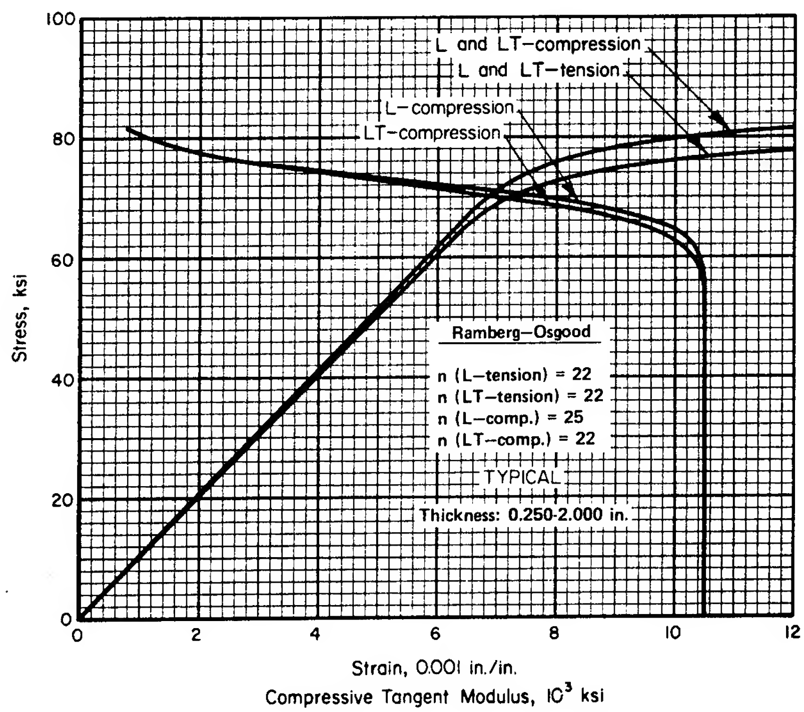

FIGURE 3.7.4.1.6(i). *Typical tensile and compressive stress-strain and compressive tangent-modulus curves for 7075-T62 aluminum alloy plate at room temperature.*

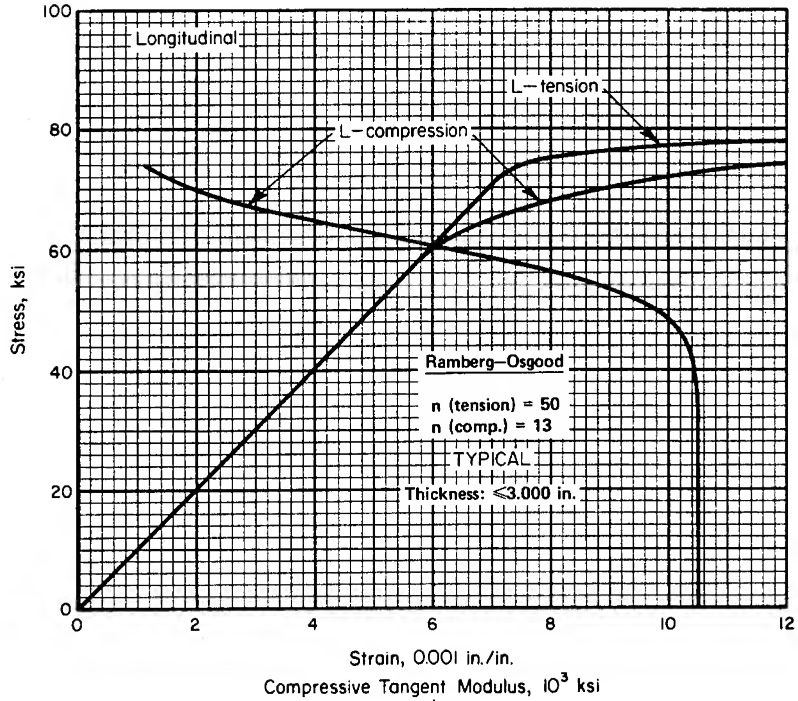

FIGURE 3.7.4.1.6(j). *Typical tensile and compressive stress-strain and compressive tangent-modulus curves for 7075-T6 and T651 aluminum alloy rolled-bar, rod, and shape at room temperature.*

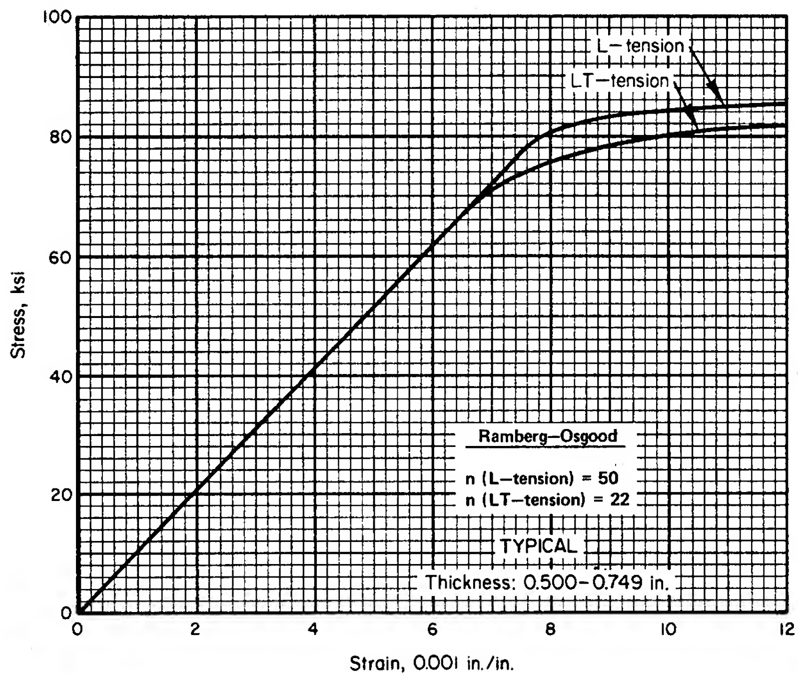

FIGURE 3.7.4.1.6(k). *Typical tensile stress-strain curves for 7075-T651X aluminum alloy extrusion at room temperature.*

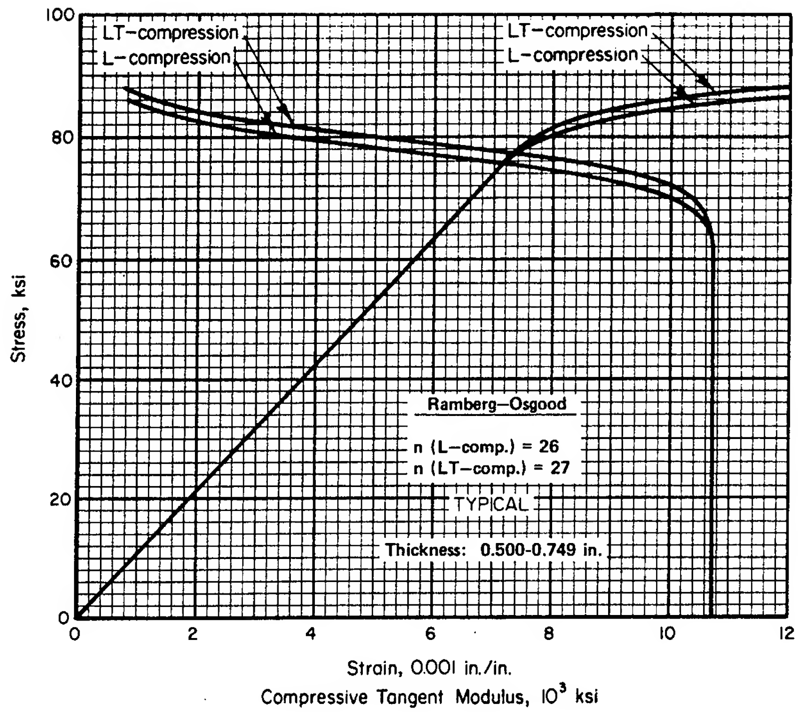

FIGURE 3.7.4.1.6(l). *Typical compressive stress-strain and compressive tangent-modulus curve for 7075-T651X aluminum alloy extrusion at room temperature.*

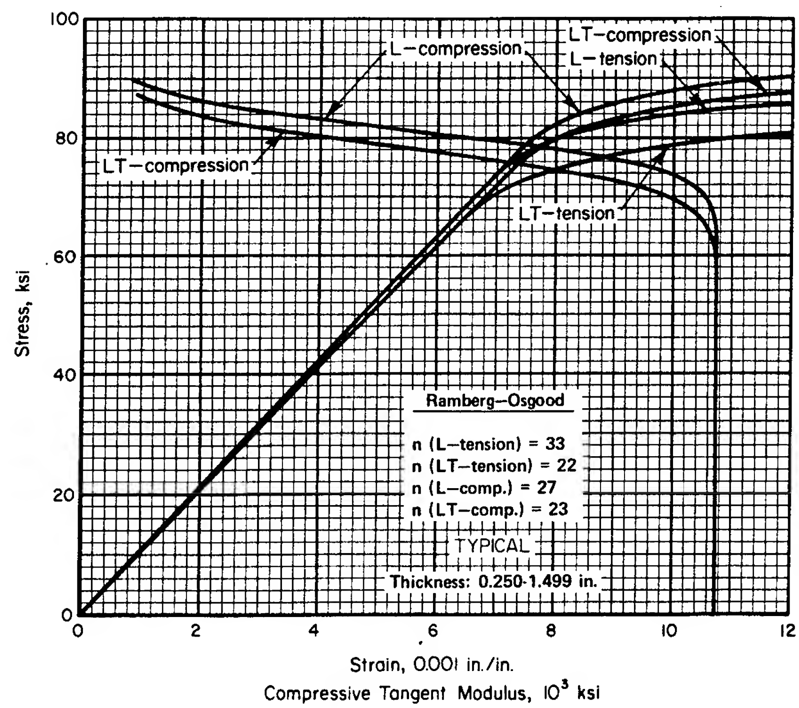

FIGURE 3.7.4.1.6(m). *Typical tensile and compressive stress-strain and compressive tangent-modulus curves for 7075-T62 aluminum alloy extrusion at room temperature.*

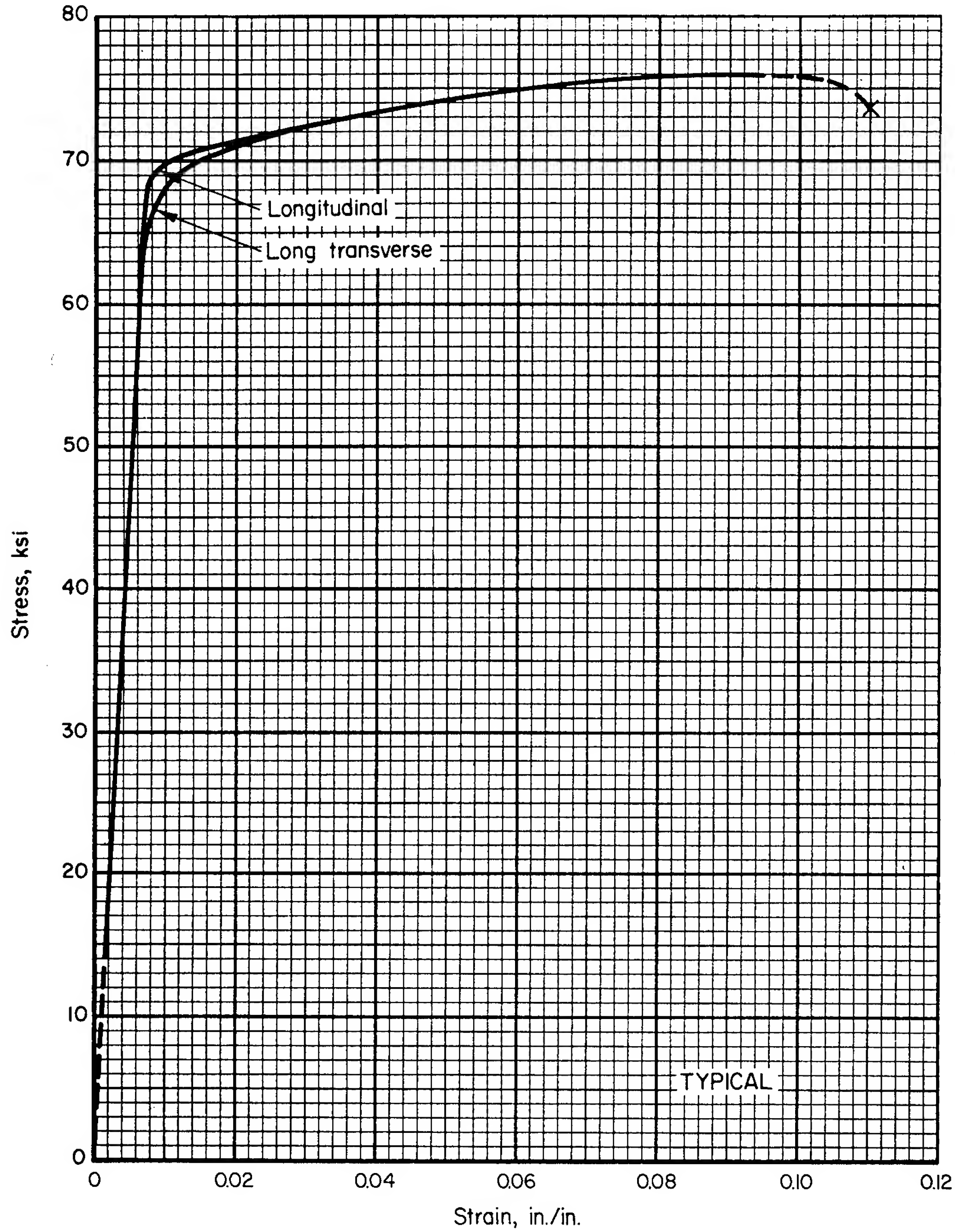

FIGURE 3.7.4.1.6(n). *Typical tensile stress-strain curve (full range) for clad 7075-T6 aluminum alloy sheet at room temperature.*

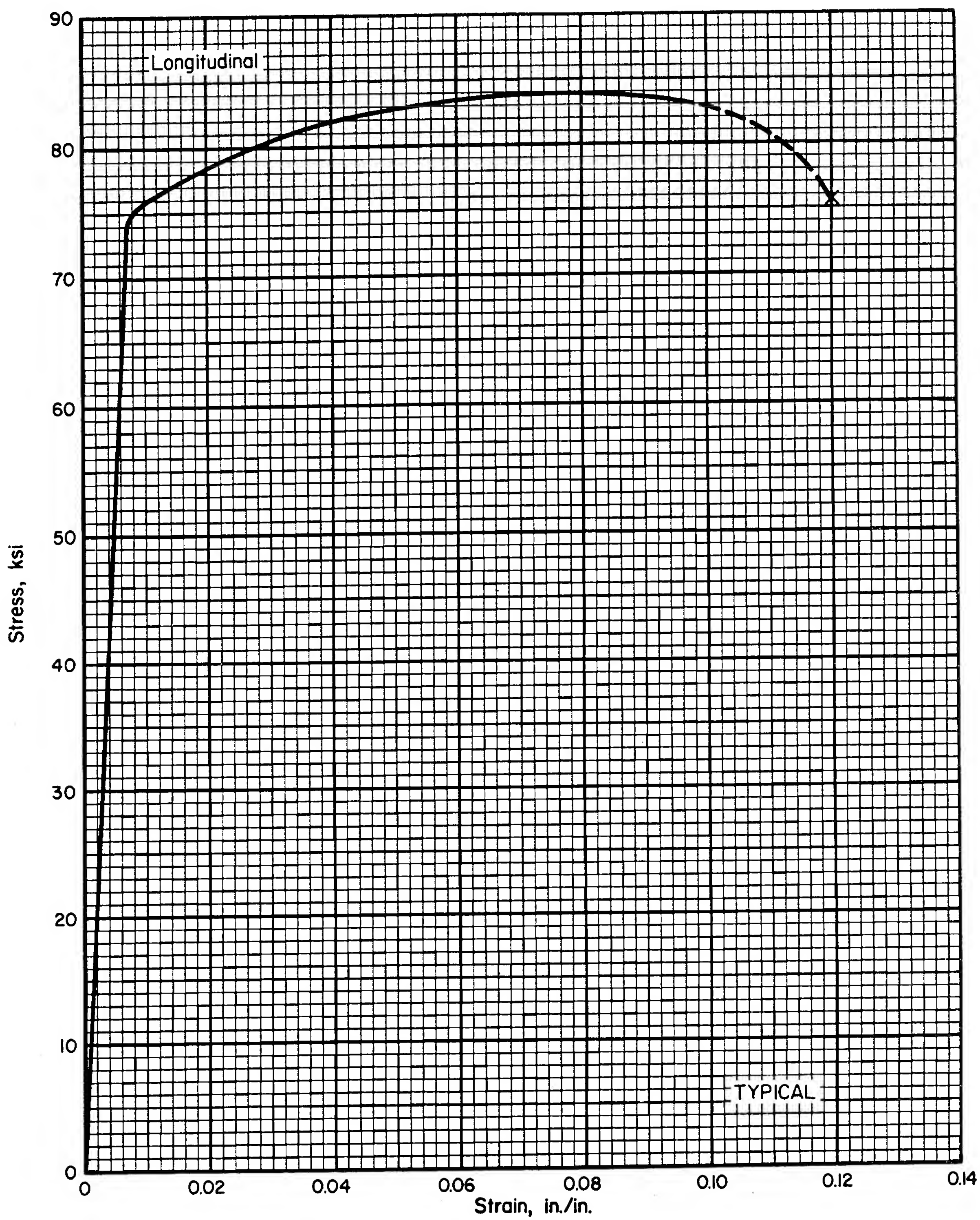

FIGURE 3.7.4.1.6(o). *Typical tensile stress-strain curve (full range) for 7075-T6 and T651 aluminum alloy rolled or cold-finished bar at room temperature.*

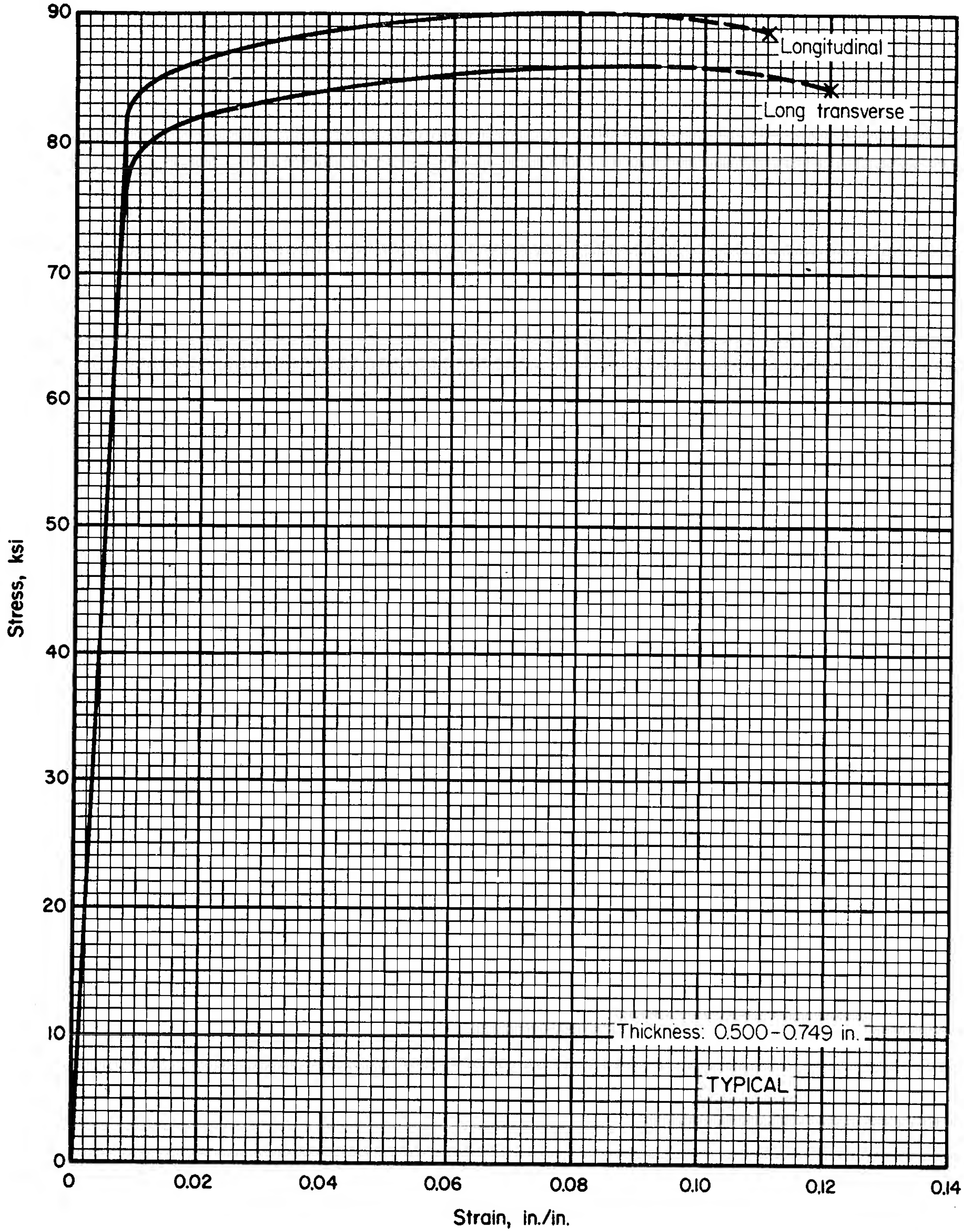

FIGURE 3.7.4.1.6(p). *Typical tensile stress-strain curves (full range) for 7075-T651X aluminum alloy extrusion at room temperature.*

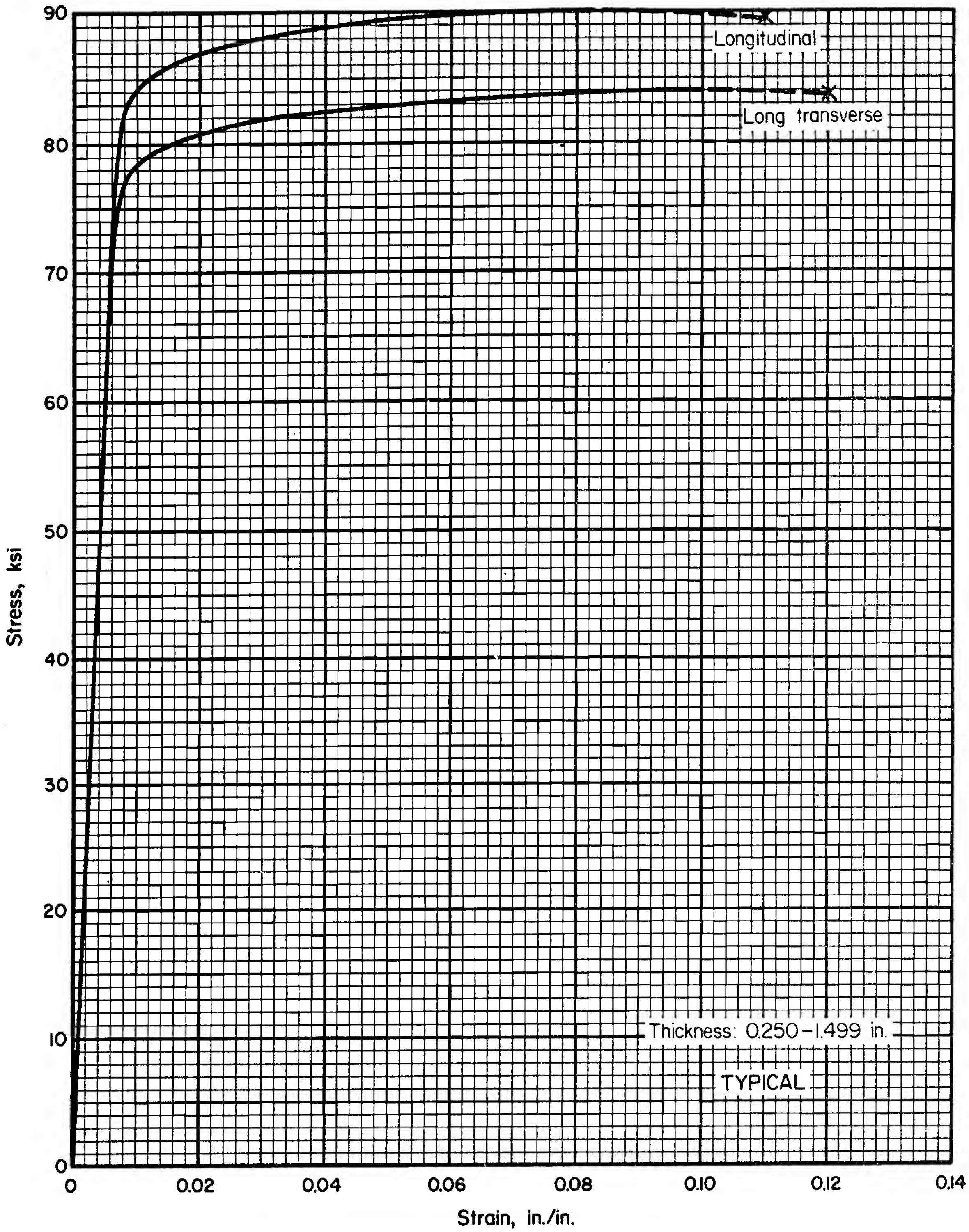

FIGURE 3.7.4.1.6(q). *Typical tensile stress-strain curves (full range) for 7075-T62 aluminum alloy extrusion at room temperature.*

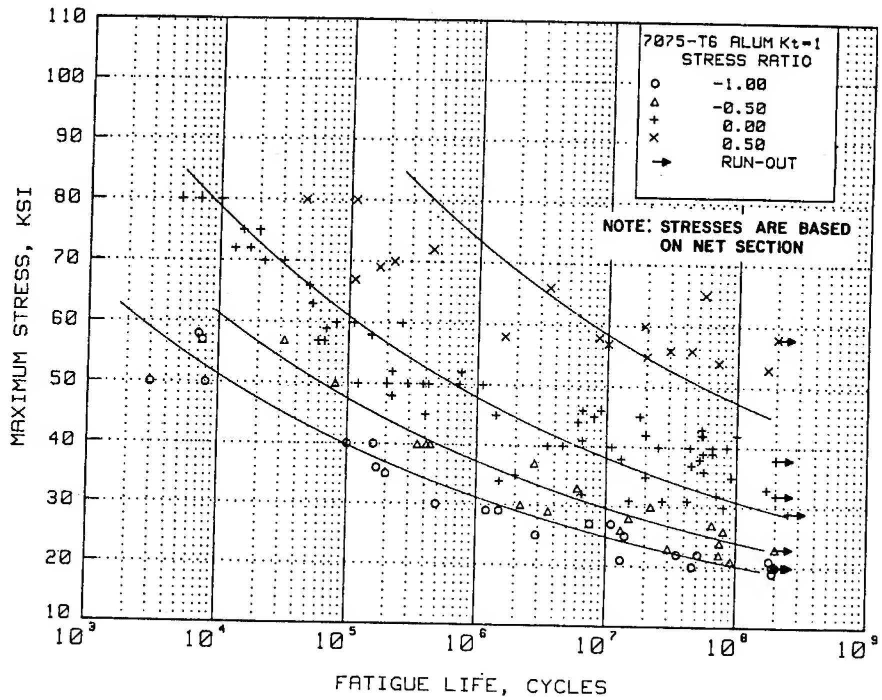

FIGURE 3.7.4.1.8(a). *Best-fit S/N curves for unnotched 7075-T6 aluminum alloy, various product forms, longitudinal direction.*

Correlative Information for Figure 3.7.4.1.8(a)

Product Form: 3/4″ diam. drawn rod, 1-1/4″ diam. rolled rod, and 1 x 7-1/2″ bar, extruded 1-1/4″ bar and 1-1/4″ rod

Properties:

TUS, ksi	TYS, ksi	Temp., F
82	72	RT

Specimen Details: Unnotched
Minimum diameter 0.200 inches

Surface Condition: Unspecified

Reference: 3.7.4.1.8

Test Parameters:

Loading — Axial
Frequency — 30 Hz
Temperature — RT
Atmosphere — Air

No. of Heats/Lots: 8

Equivalent Stress Equation

Log N_f = 18.21−7.73 log (S_{eq}-10)
$S_{eq} = S_{max} (1-R)^{0.62}$
R^2 = 81%
Sample Size = 130

[Caution: The equivalent stress model may provide unrealistic life predictions for stress ratios beyond those represented above]

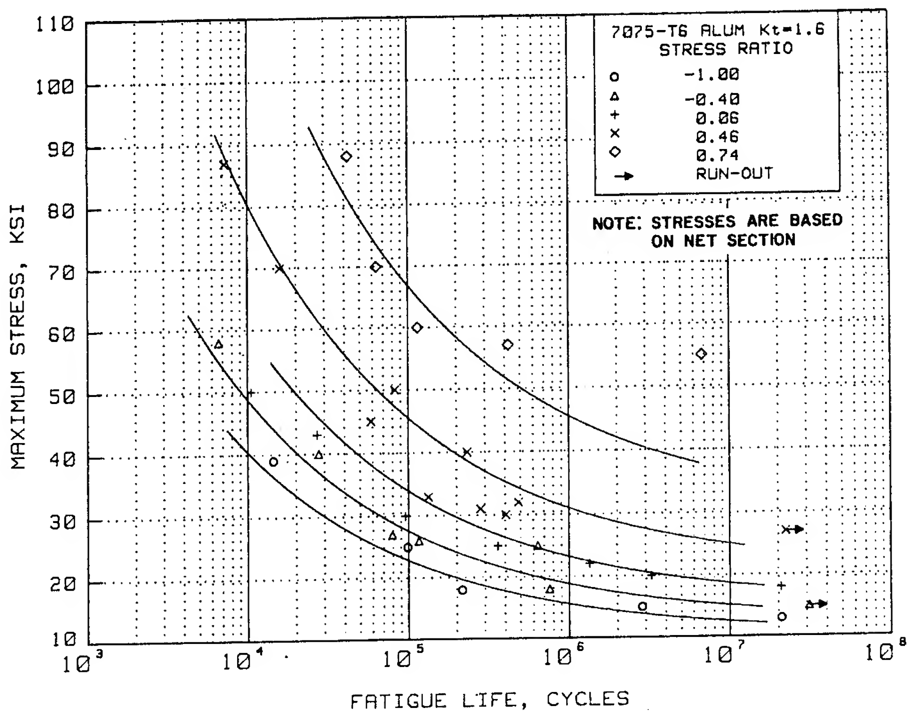

FIGURE 3.7.4.1.8(b). *Best-fit S/N curves for notched, K_t = 1.6, 7075-T6 aluminum alloy rolled bar, longitudinal direction.*

Correlative Information for Figure 3.7.4.1.8(b)

Product Form: 1-1/8″ diam. rolled bar

Properties:

TUS, ksi	TYS, ksi	Temp., F
99.2	—	RT

Specimen Details: Notched, K_t = 1.6
Notch-root-radius = 0.100
Test section diameter (Net) = 0.400 inches
Gross diameter = 0.450 inches
60° groove

Surface Condition: Polished to 10 micro-inches

Reference: 3.2.1.1.8(b)

Test Parameters:

Loading — Axial
Frequency — 60
Temperature — RT
Atmosphere — Air

No. of Heats/Lots: 1

Equivalent Stress Equation

$\text{Log } N_f = 8.28-2.62 \log (S_{eq}-15)$
$S_{eq} = S_{max} (1-R)^{0.53}$
$R^2 = 82\%$
Sample Size = 34

[Caution: The equivalent stress model may provide unrealistic life predictions for stress ratios beyond those represented above]

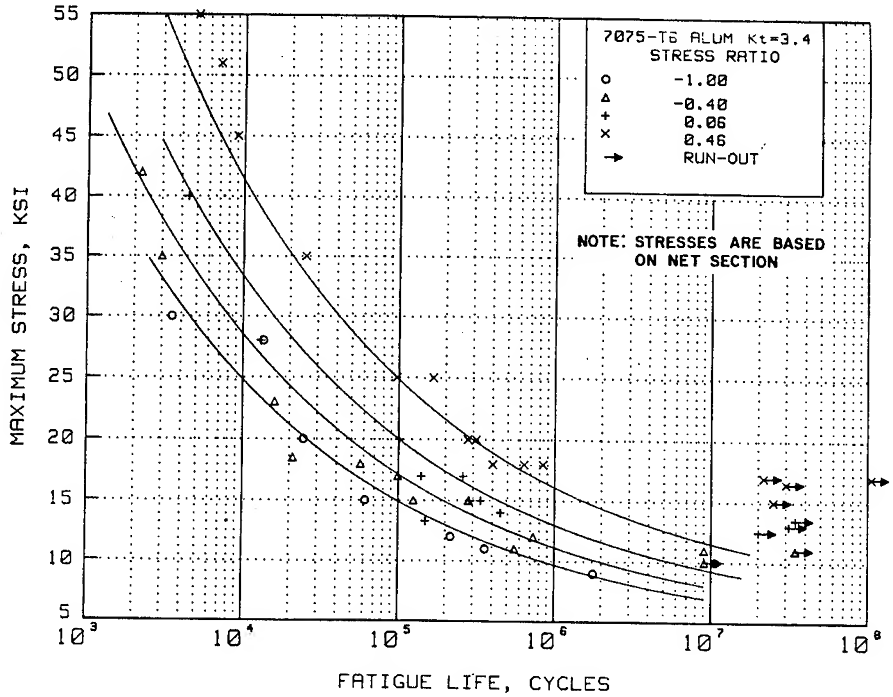

FIGURE 3.7.4.1.8(c). *Best-fit S/N curves for notched, K_t = 3.4, 7075-T6 aluminum alloy rolled bar, longitudinal direction.*

Correlative Information for Figure 3.7.4.1.8(c)

Product Form: 1-1/8″ diam. rolled bar

Properties:

TUS, ksi	TYS, ksi	Temp., F
96.5	—	RT

Specimen Details: Notched, K_t = 3.4
Notch-root-radius = 0.010
Test section diameter (Net) = 0.400 inches
Gross diameter = 0.450 inches
60° groove

Surface Condition: Polished to 10 micro-inches

Reference: 3.2.1.1.8(b)

Test Parameters:
Loading — Axial
Frequency — 60 Hz
Temperature — RT
Atmosphere — Air

No. of Heats/Lots: 1

Equivalent Stress Equation

$\log N_f = 9.19 - 3.60 \log (S_{eq} - 5)$
$S_{eq} = S_{max} (1-R)^{0.39}$
$R^2 = 87\%$
Sample Size = 48

[Caution: The equivalent stress model may provide unrealistic life predictions for stress ratios beyond those represented above]

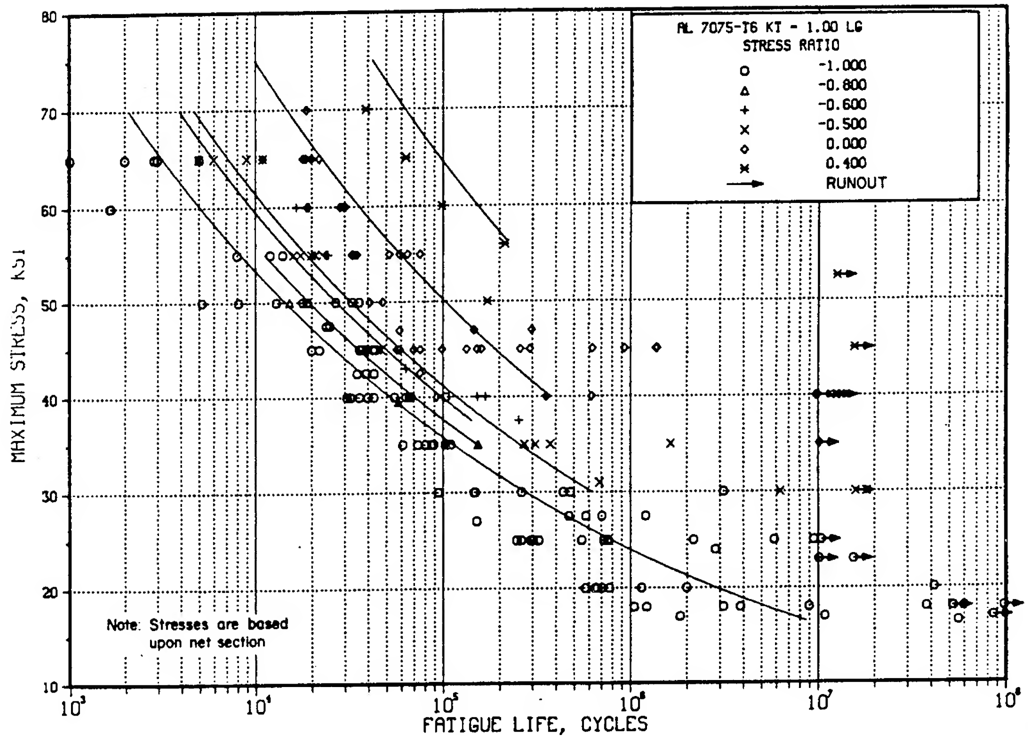

FIGURE 3.7.4.1.8(d). *Best-fit S/N curves for unnotched 7075-T6 aluminum alloy sheet, longitudinal direction.*

Correlative Information for Figure 3.7.4.1.8(d)

Product Form: Bare sheet, 0.090 inch

Properties:	TUS, ksi	TYS, ksi	Temp., F
	82	76	RT

Specimen Details: Unnotched
0.5-1.0-inch width

Surface Condition: Electropolished
150 grit energy paper

References: 3.2.3.1.8(a), and (f)

Test Parameters:

Loading - Axial
Frequency - 300 to 1800 cpm
Environment - Air

No. of Heats/Lots: Not specified

Equivalent Stress Equation:

Log N_f = 14.86-5.80 log (S_{eq})
$S_{eq} = S_{max} (1-R)^{0.49}$
Standard Error of Estimate = 0.41
Standard Deviation in Life = 0.92
R^2 = 80%

Sample Size = 176

[Caution: The equivalent stress model may provide unrealistic life predictions for stress ratios beyond those represented above]

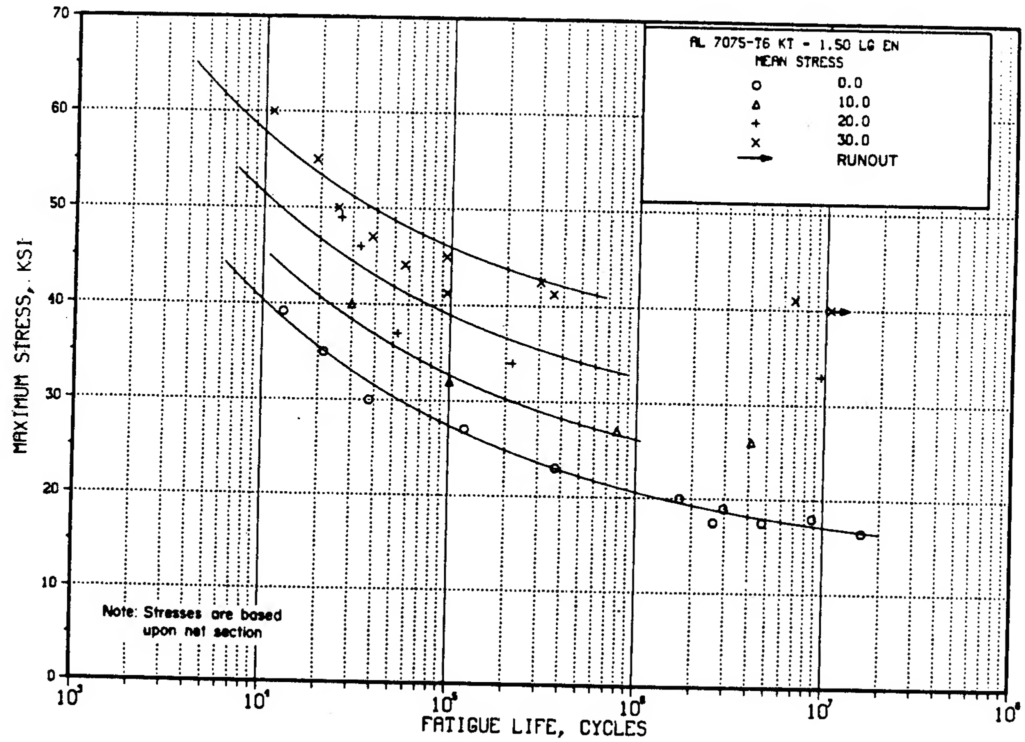

FIGURE 3.7.4.1.8(e). *Best-fit S/N curves for notched, $K_t = 1.5$, 7075-T6 aluminum alloy sheet, longitudinal direction.*

Correlative Information for Figure 3.7.4.1.8(e)

Product Form: Bare sheet, 0.090 inch

Properties:

TUS, ksi	TYS, ksi	Temp., F
82	76	RT (unnotched)
87	—	RT (notched)

Specimen Details: Edge Notched

3.000 inches gross width
1.500 inches net width
0.760 inch notch radius
0° flank angle

Surface Condition: Electropolished

Reference: 3.2.3.1.8(d)

Test Parameters:

Loading - Axial
Frequency - 1100 to 1500 cpm
Temperature - RT
Environment - Air

No. of Heats/Lots: Not specified

Equivalent Stress Equation:

$\text{Log } N_f = 9.57 - 3.52 \log (S_{eq} - 18.7)$
$S_{eq} = S_{max} (1\text{-}R)^{0.49}$
Standard Error of Estimate = 0.41
Standard Deviation in Life = 1.00
$R^2 = 83\%$

Sample Size = 30

[Caution: The equivalent stress model may provide unrealistic life predictions for stress ratios beyond those represented above]

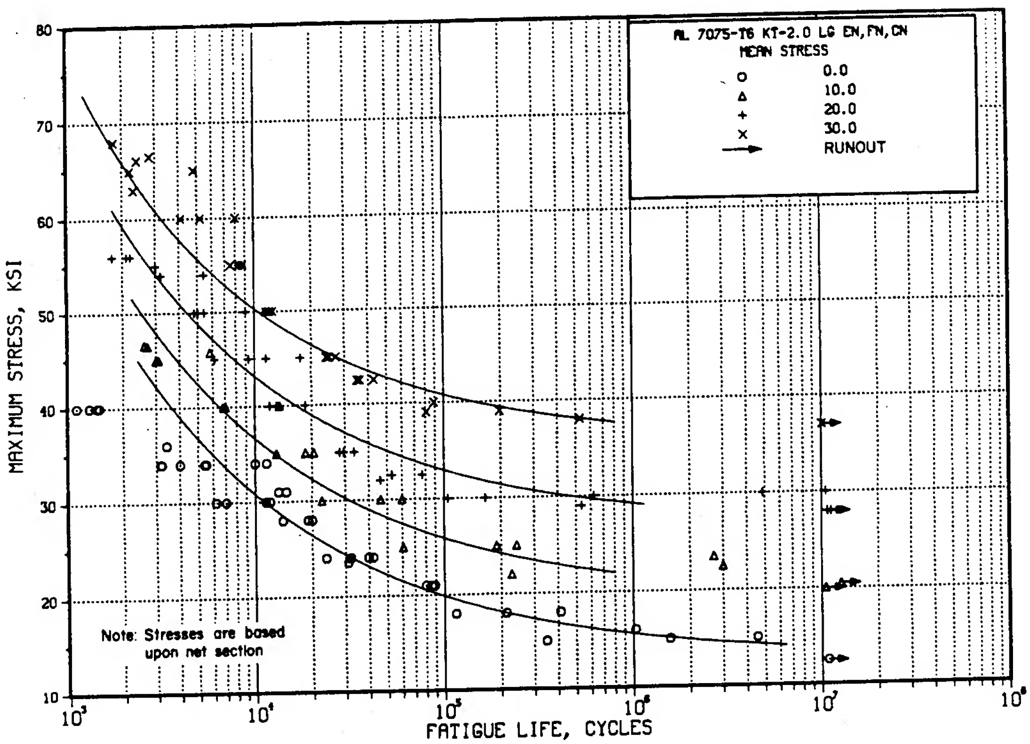

FIGURE 3.7.4.1.8(f). *Best-fit S/N curves for notched, K_t = 2.0, 7075-T6 aluminum alloy sheet, longitudinal direction.*

Correlative Information for Figure 3.7.4.1.8(f)

Product Form: Bare sheet, 0.090 inch

Properties:	TUS, ksi	TYS, ksi	Temp., F
	82	76	RT (unnotched)
	88	—	RT (notched)

Specimen Details: Notched

Notch Type	Gross Width	Net Width	Notch Radius
Center	4.50	1.50	1.50
Edge	2.25	1.50	0.3175
Fillet	2.25	1.50	0.1736

Surface Condition: Electropolished

References: 3.2.3.1.8(b) and (f)

Test Parameters:

Loading – Axial
Frequency – 1100 to 1500 cpm
Temperature – RT
Environment – Air

No. of Heats/Lots: Not specified

Equivalent Stress Equation:

Log N_f = 7.50–2.46 log (S_{eq} – 18.6)
$S_{eq} = S_{max} (1-R)^{0.54}$
Standard Error of Estimate = 0.31
Standard Deviation in Life = 0.85
R^2 = 57%

Sample Size = 112

[Caution: The equivalent stress model may provide unrealistic life predictions for stress ratios beyond those represented above]

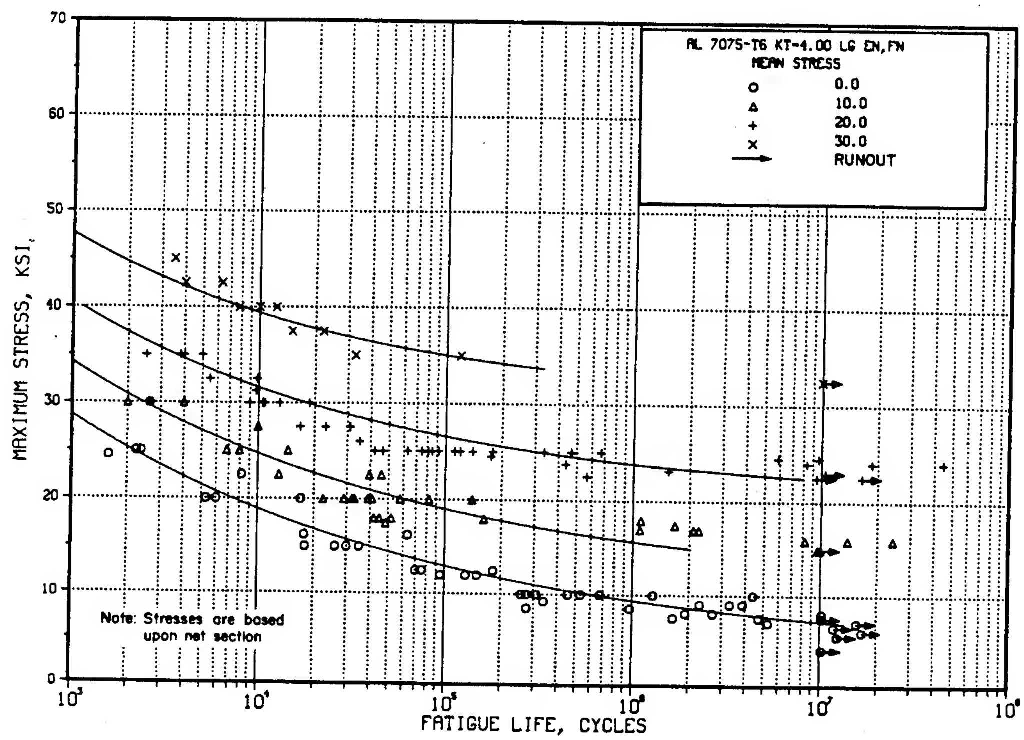

FIGURE 3.7.4.1.8(g). *Best-fit S/N curves for notched, K_t = 4.0, 7075-T6 aluminum alloy sheet, longitudinal direction.*

Correlative Information for Figure 3.7.4.1.8(g)

Product Form: Bare sheet, 0.090 inch

Properties:

TUS, ksi	TYS, ksi	Temp., F
82	76	RT (unnotched)
82	—	RT (notched)

Specimen Details: Notched

Notch Type	Gross Width	Net Width	Notch Radius
Edge	2.25	1.500	0.057
Edge	4.10	1.500	0.070
Fillet	2.25	1.500	0.0195

Surface Condition: Electropolished

Reference: 3.2.3.1.8(b), (f), (g), and (h)

Test Parameters:

Loading – Axial
Frequency – 1100 to 1800 cpm
Temperature – RT
Environment – Air

No. of Heats/Lots: Not specified

Equivalent Stress Equation:

Log N_f = 10.2–4.63 log (S_{eq} – 5.3)
$S_{eq} = S_{max} (1-R)^{0.51}$
Standard Error of Estimate = 0.51
Standard Deviation in Life = 1.08
R^2 = 78%

Sample Size = 126

[Caution: The equivalent stress model may provide unrealistic life predictions for stress ratios beyond those represented above]

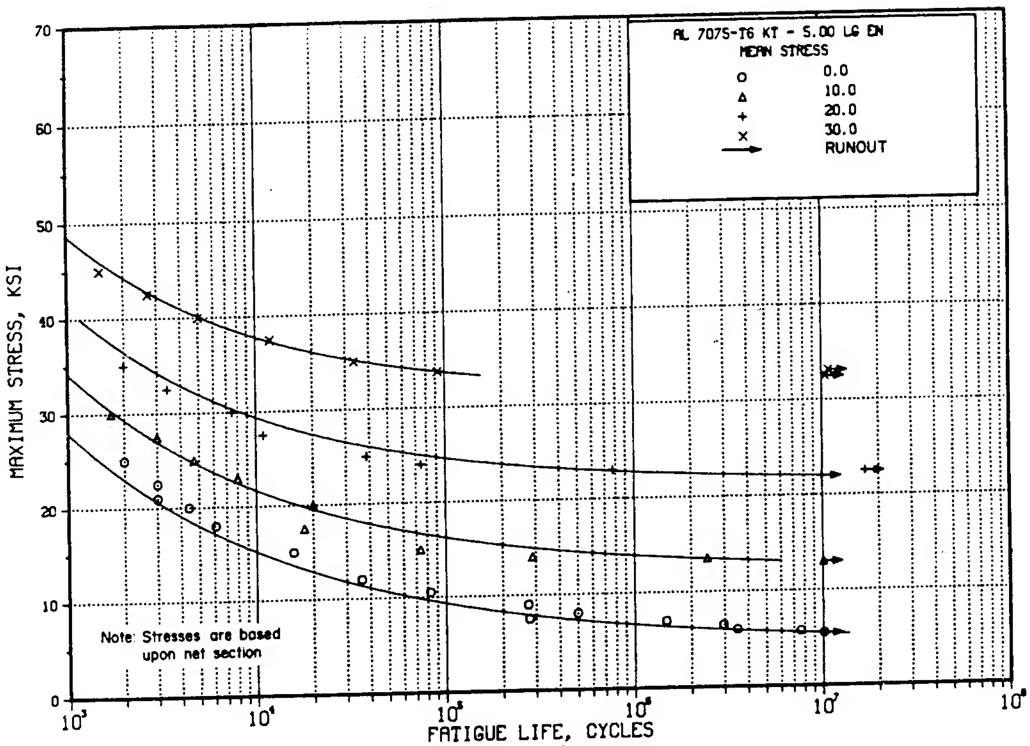

FIGURE 3.7.4.1.8(h). *Best-fit S/N curves for notched, K_t = 5.0, 7075-T6 aluminum alloy sheet, longitudinal direction.*

Correlative Information for Figure 3.7.4.1.8(h)

Product Form: Bare sheet, 0.090 inch

Properties:	TUS, ksi	TYS, ksi	Temp., F
	82	76	RT (unnotched)
	77	—	RT (notched)

Specimen Details: Edge Notched
2.25 inches gross width
1.500 inches net width
0.3125 inch notch radius

Surface Condition: Electropolished

Reference: 3.2.3.1.8(c)

Test Parameters:

Loading – Axial
Frequency – 1100 to 1500 cpm
Temperature – RT
Environment – Air

No. of Heats/Lots: Not specified

Equivalent Stress Equation:

Log N_f = 7.51–2.92 log (S_{eq} – 6.7)
$S_{eq} = S_{max} (1\text{-}R)^{0.58}$
Standard Error of Estimate = 0.23
Standard Deviation in Life = 1.08
R^2 = 95%

Sample Size = 37

[Caution: The equivalent stress model may provide unrealistic life predictions for stress ratios beyond those represented above]

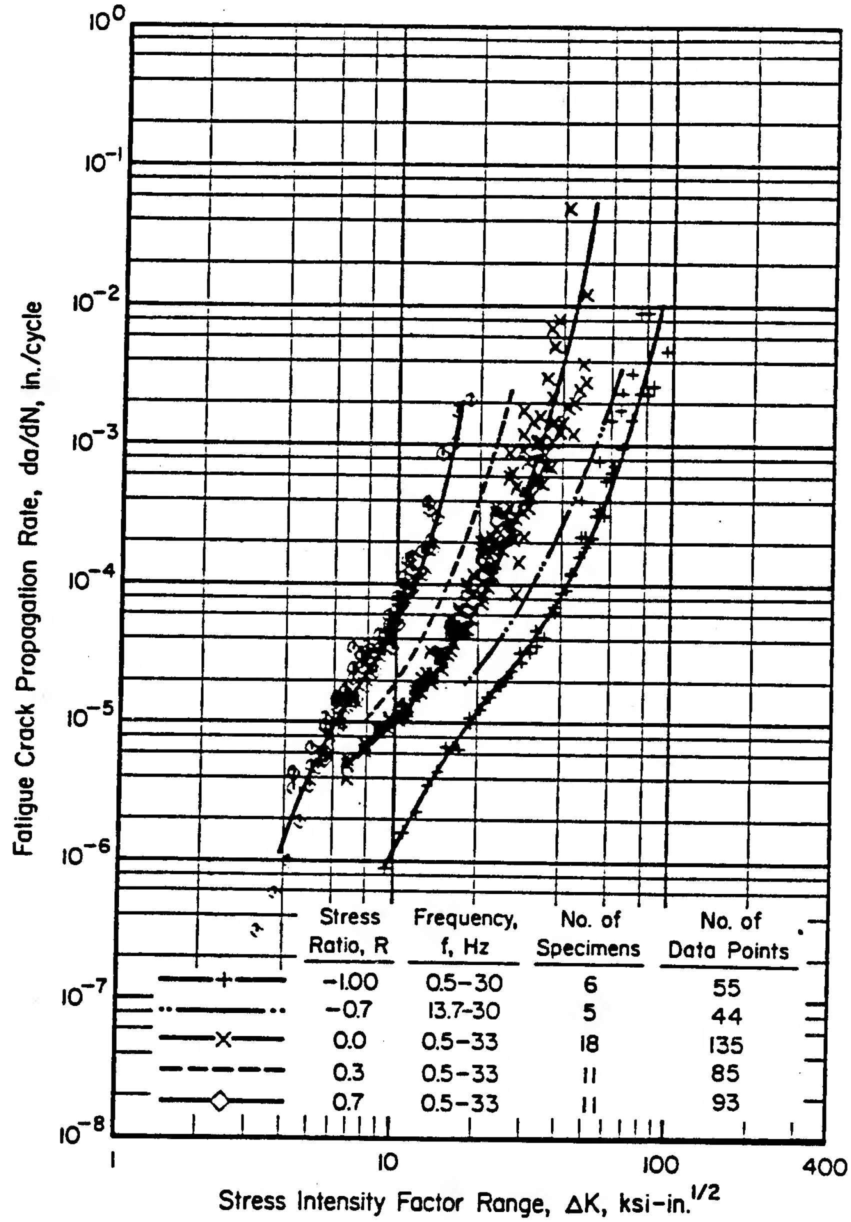

FIGURE 3.7.4.1.9. *Fatigue-crack-propagation data for 0.090-inch-thick 7075-T6 aluminum alloy sheet with buckling restraint. [References 3.7.4.1.9(a) through (e)].*

Specimen Thickness:	*0.090 inch*	*Environment:*	*Lab Air*
Specimen Width:	*1½-12 inches*	*Temperature:*	*RT*
Specimen Type:	*CC*	*Orientation:*	*L-T*

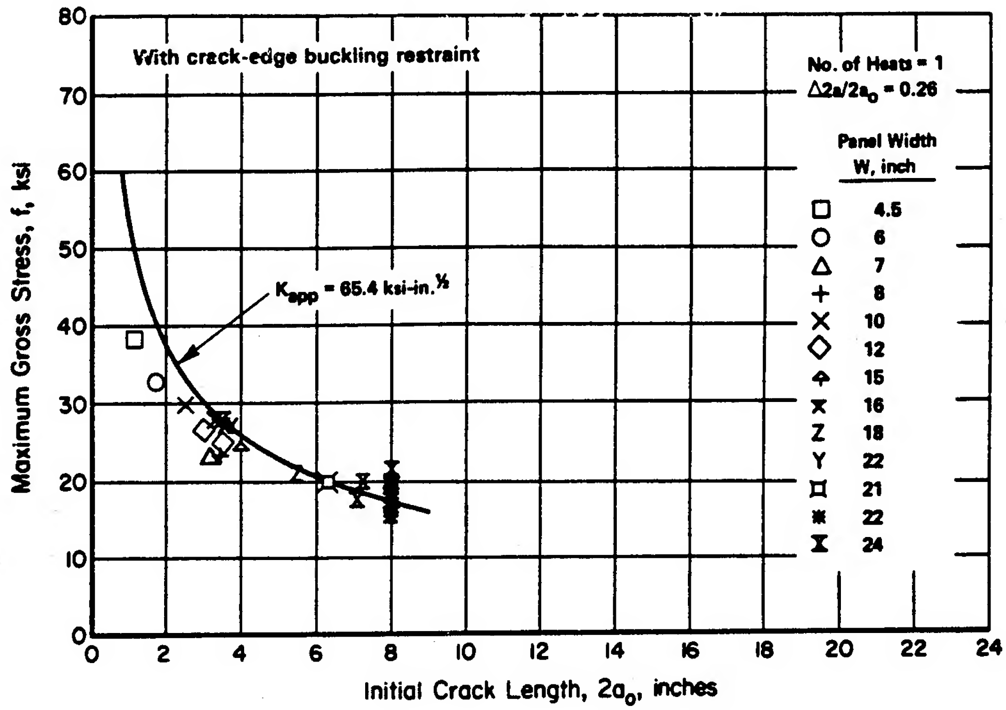

FIGURE 3.7.4.1.10(a). *Residual strength behavior of 0.063-inch-thick 7075-T6 aluminum alloy sheet at room temperature. Crack orientation is T-L.* [*Reference 3.1.2.1.6(f)*).

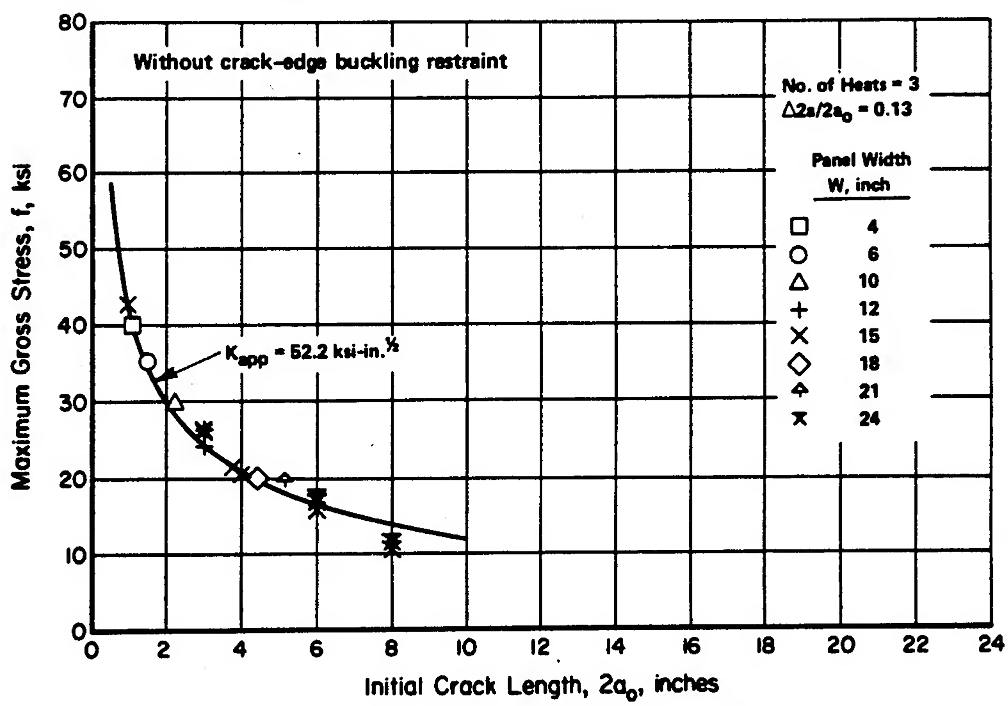

FIGURE 3.7.4.1.10(b). *Residual strength behavior of 0.063-inch-thick 7075-T6 aluminum alloy sheet at room temperature. Crack orientation is T-L.* [*References 3.1.2.1.6(d) and (f)*].

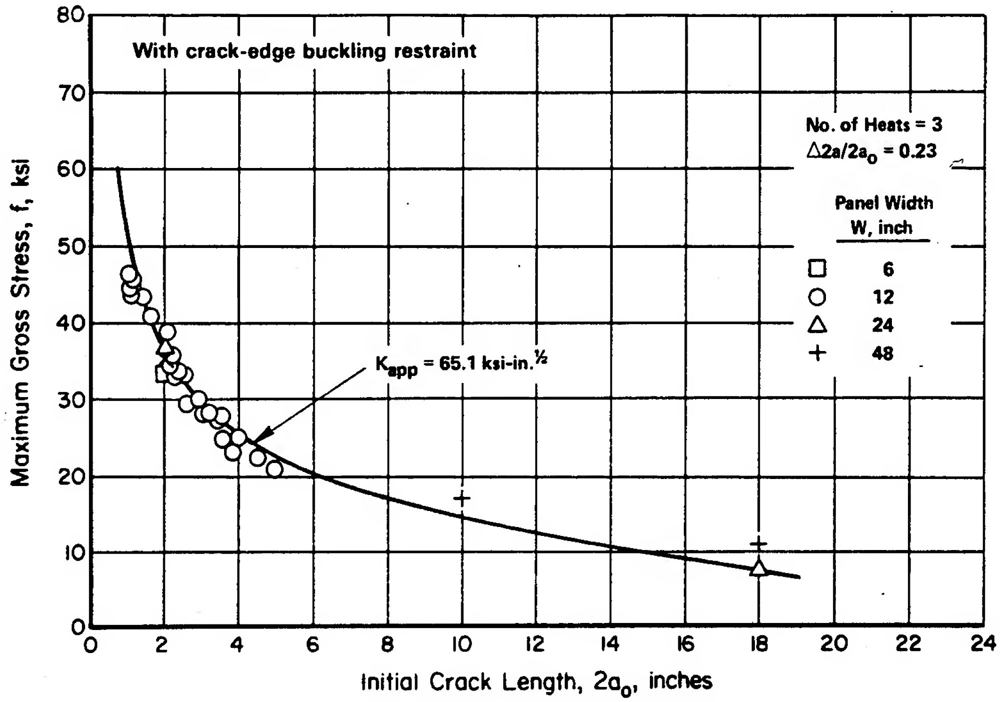

FIGURE 3.7.4.1.10(c). *Residual strength behavior of 0.090- and 0.100-inch-thick 7075-T6 alloy sheet at room temperature. Crack orientation is L-T.* [*References 3.1.2.1.6(e), (g), and 3.7.4.1.9(e)*].

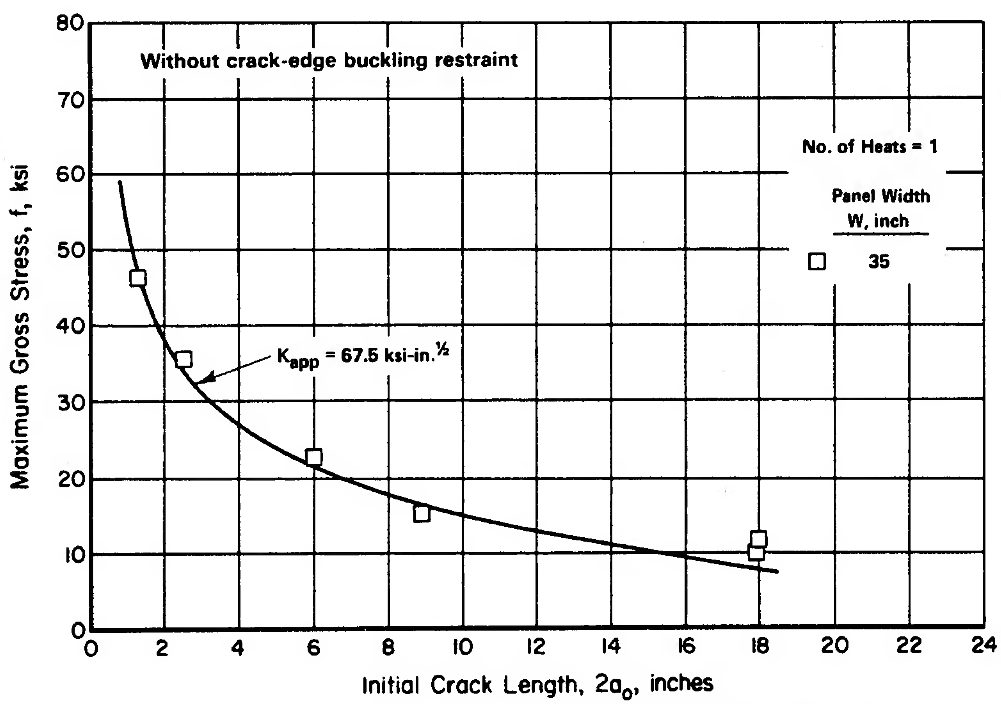

FIGURE 3.7.4.1.10(d). *Residual strength behavior of 0.100-inch-thick 7075-T6 aluminum alloy sheet at room temperature. Crack orientation is L-T.* [*Reference 3.1.2.1.6(g)*].

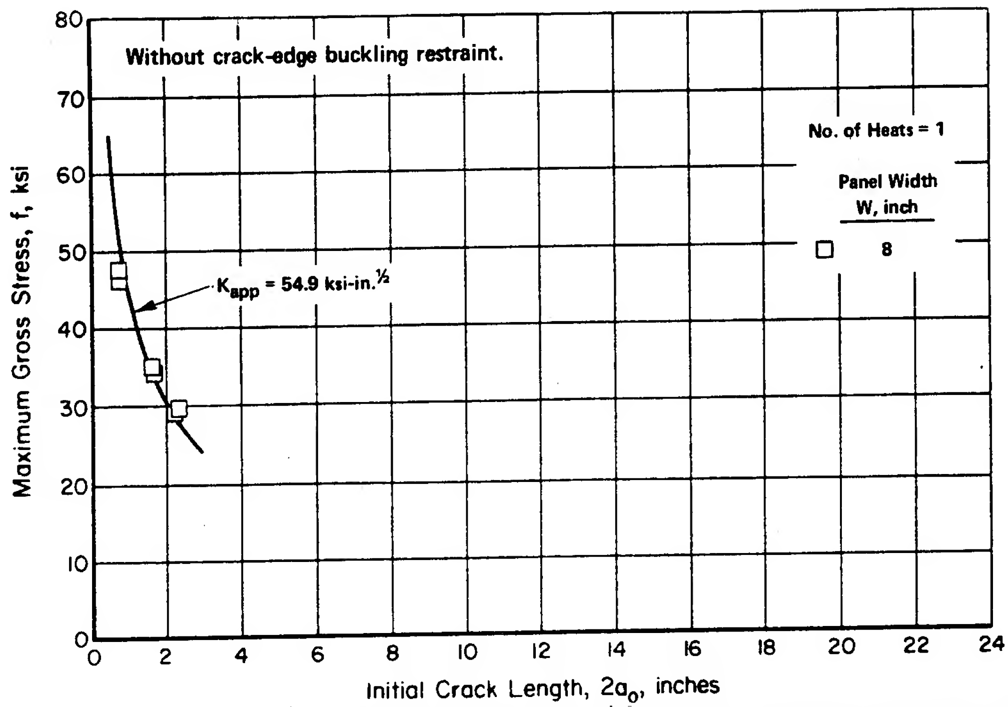

FIGURE 3.7.4.1.10(e). *Residual strength behavior of 0.313-inch-thick 7075-T6 aluminum alloy plate at room temperature. Crack orientation is L-T. [Reference 3.1.2.1.6(g)).*

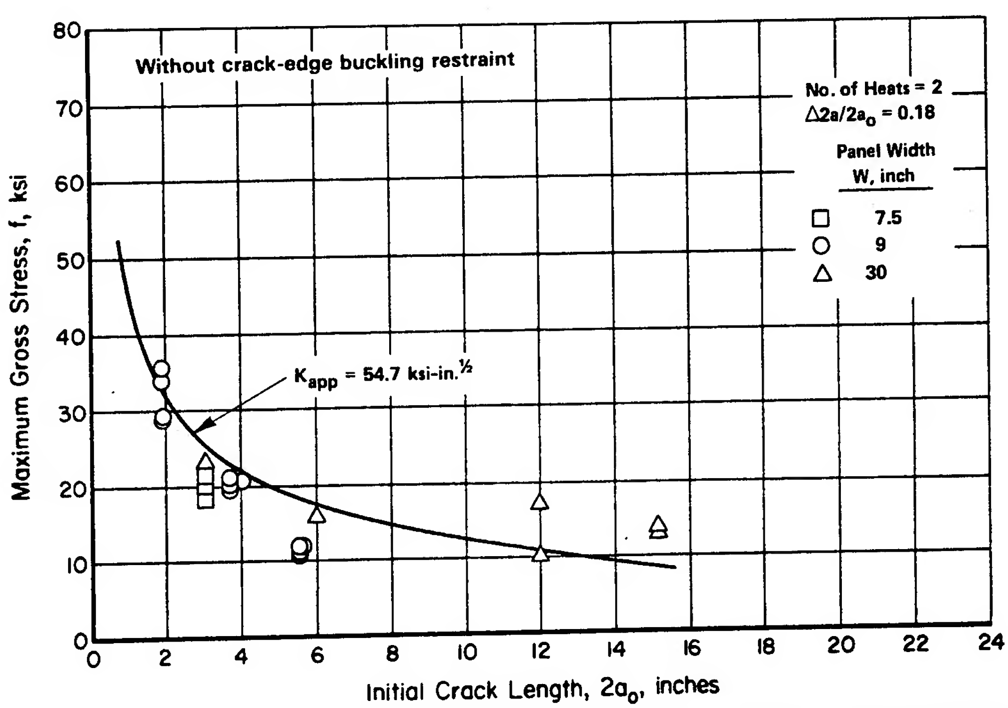

FIGURE 3.7.4.1.10(f). *Residual strength behavior of 0.040-inch-thick 7075-T6 clad aluminum alloy sheet at room temperature. Crack orientation is L-T. [References 3.1.2.1.6(f) and 3.7.4.1.10(f)].*

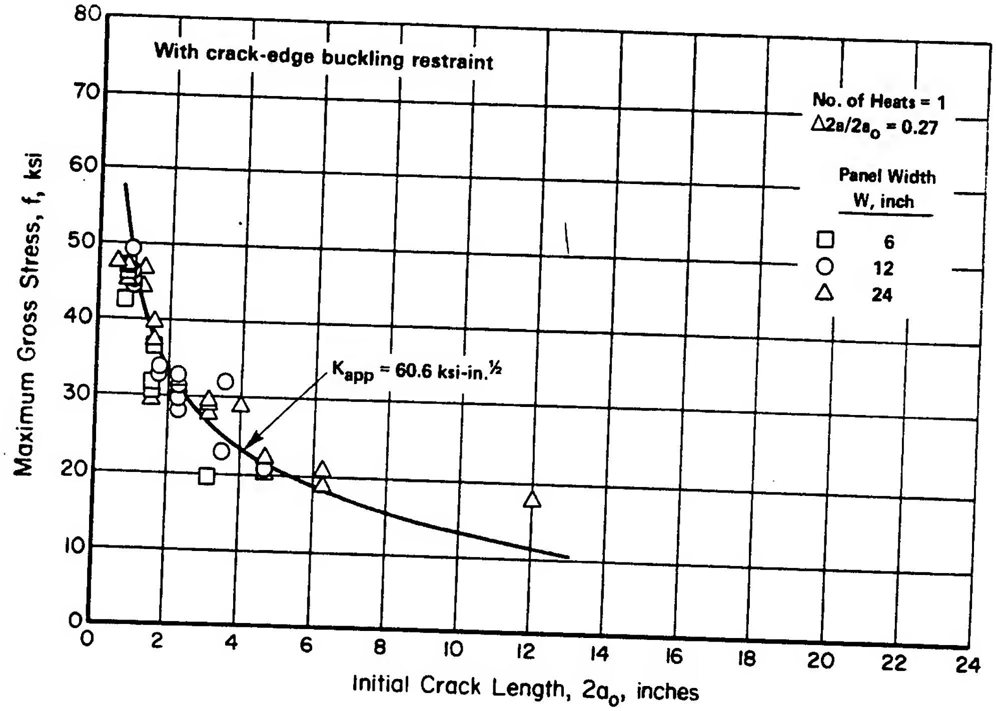

FIGURE 3.7.4.1.10(g). *Residual strength behavior of 0.080-inch-thick 7075-T6 clad aluminum alloy sheet at room temperature. Crack orientation is L-T. [References 3.1.2.1.6(h) and (i)].*

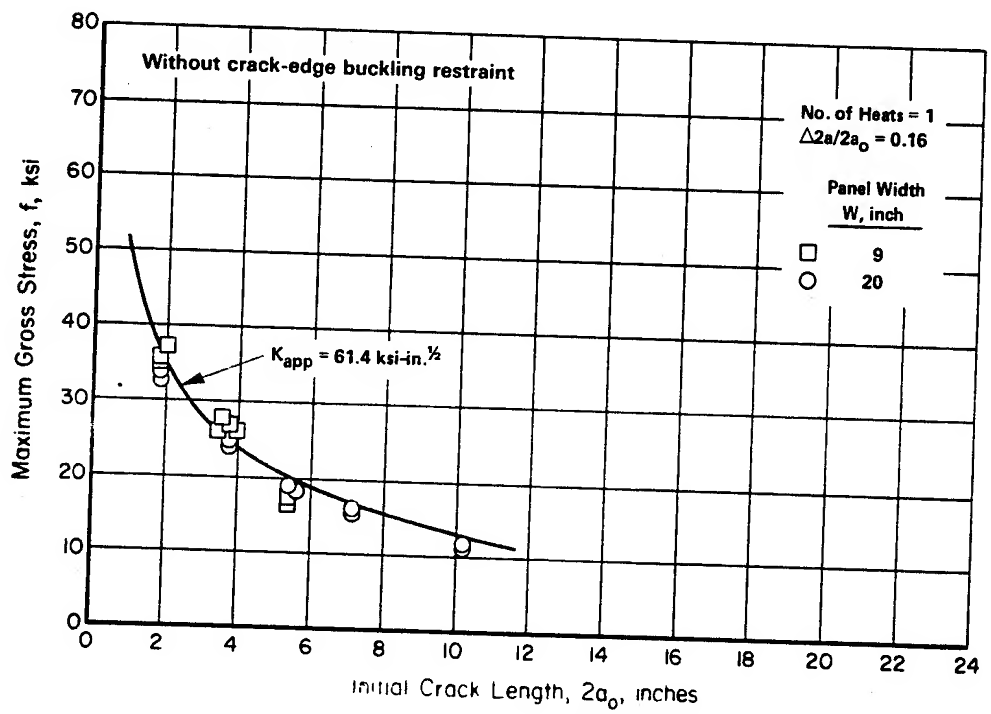

FIGURE 3.7.4.1.10(h). *Residual strength behavior of 0.090-inch-thick 7075-T6 clad aluminum alloy sheet at room temperature. Crack orientation is L-T. [Reference 3.7.4.1.10(f)].*

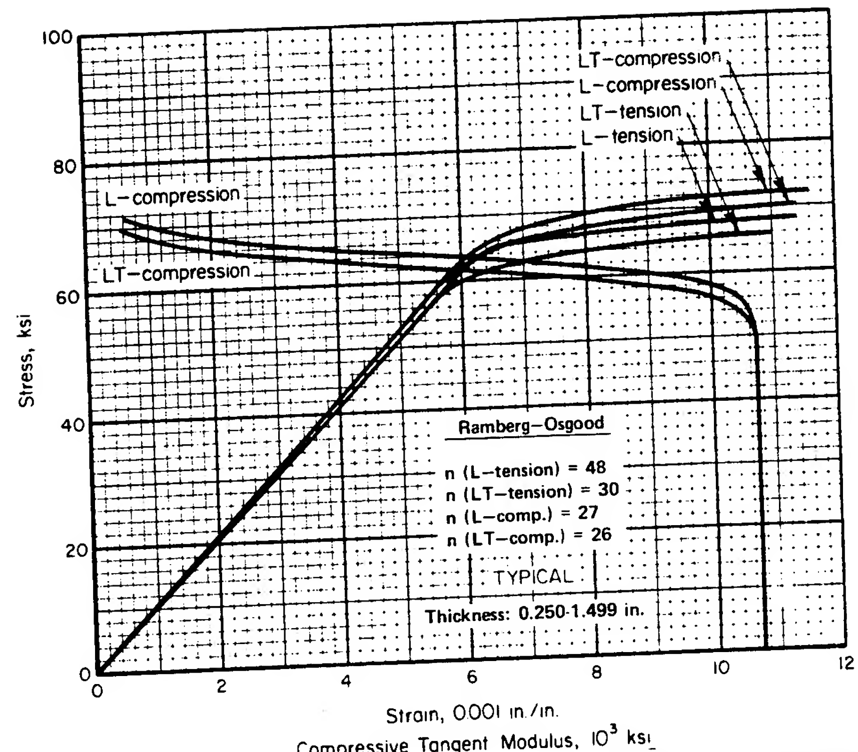

FIGURE 3.7.4.2.6(a). *Typical tensile and compressive stress-strain and compressive tangent-modulus curves for 7075-T73 aluminum alloy extrusion at room temperature.*

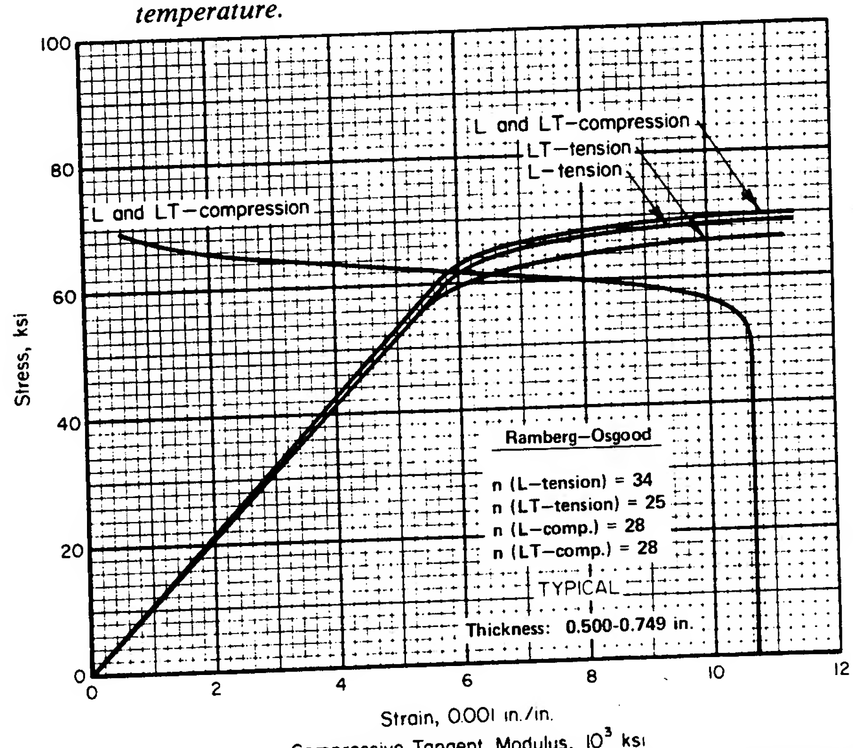

FIGURE 3.7.4.2.6(b). *Typical tensile and compressive stress-strain and compressive tangent-modulus curves for 7075-T7351X aluminum alloy extrusion at room temperature.*

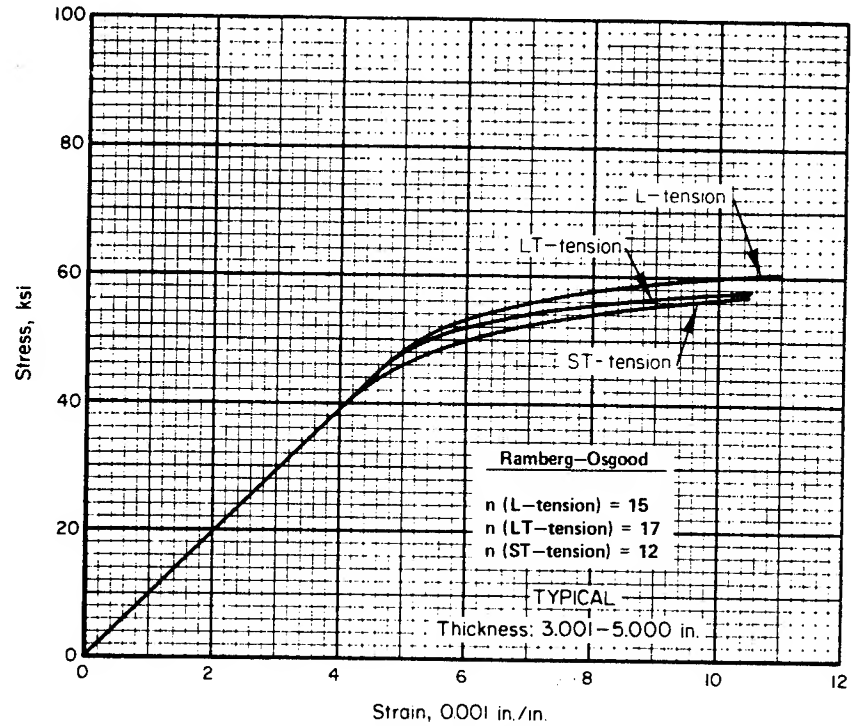

FIGURE 3.7.4.2.6(c). *Typical tensile stress-strain curves for 7075-T7352 aluminum alloy hand forging at room temperature.*

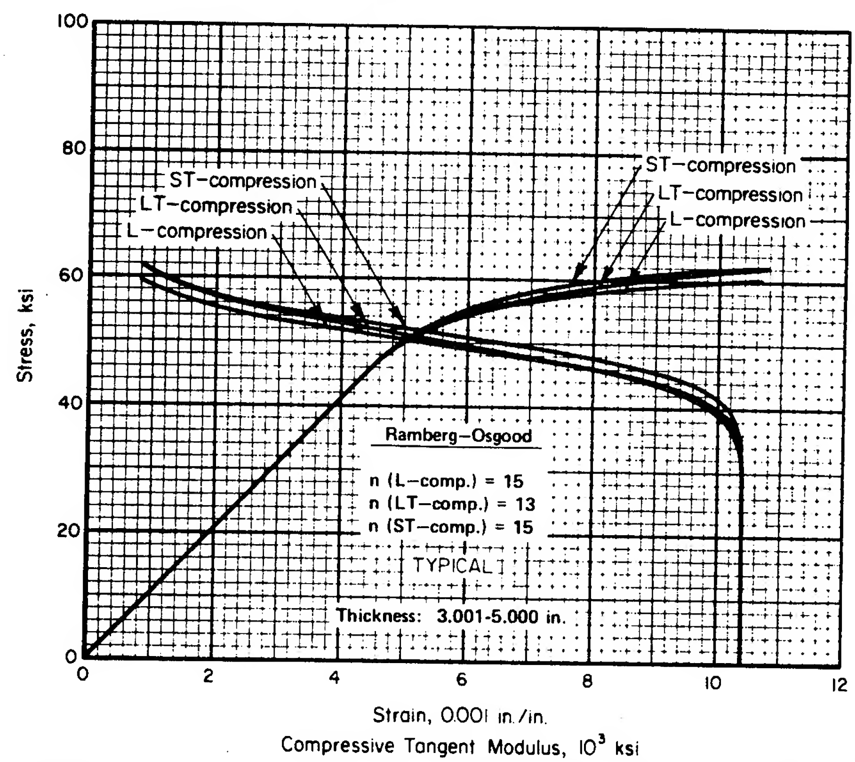

FIGURE 3.7.4.2.6(d). *Typical compressive stress-strain and compressive tangent-modulus curves for 7075-T7352 aluminum alloy hand forging at room temperature.*

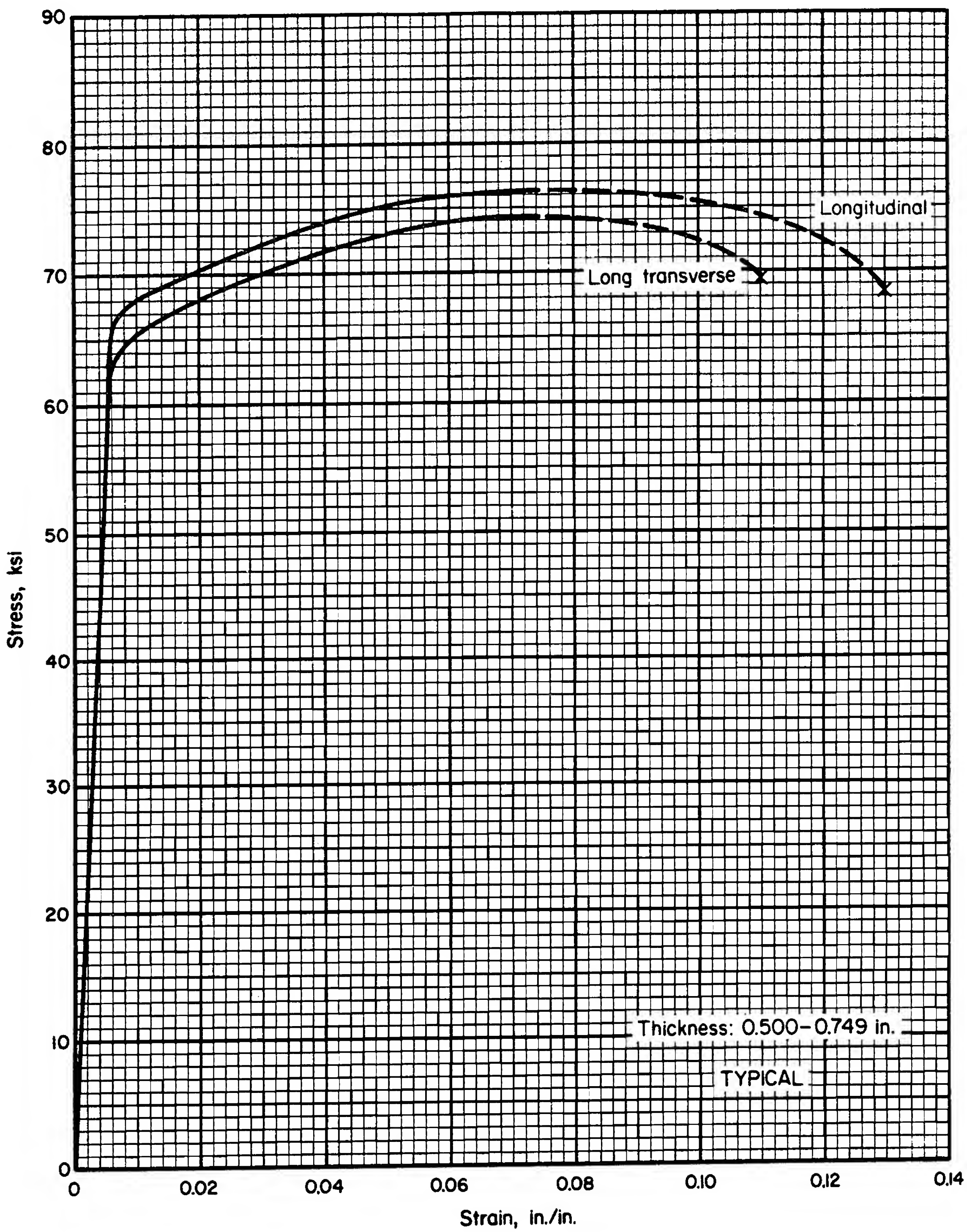

FIGURE 3.7.4.2.6(e). *Typical tensile stress-strain curves (full range) for 7075-T7351X aluminum alloy extrusion at room temperature.*

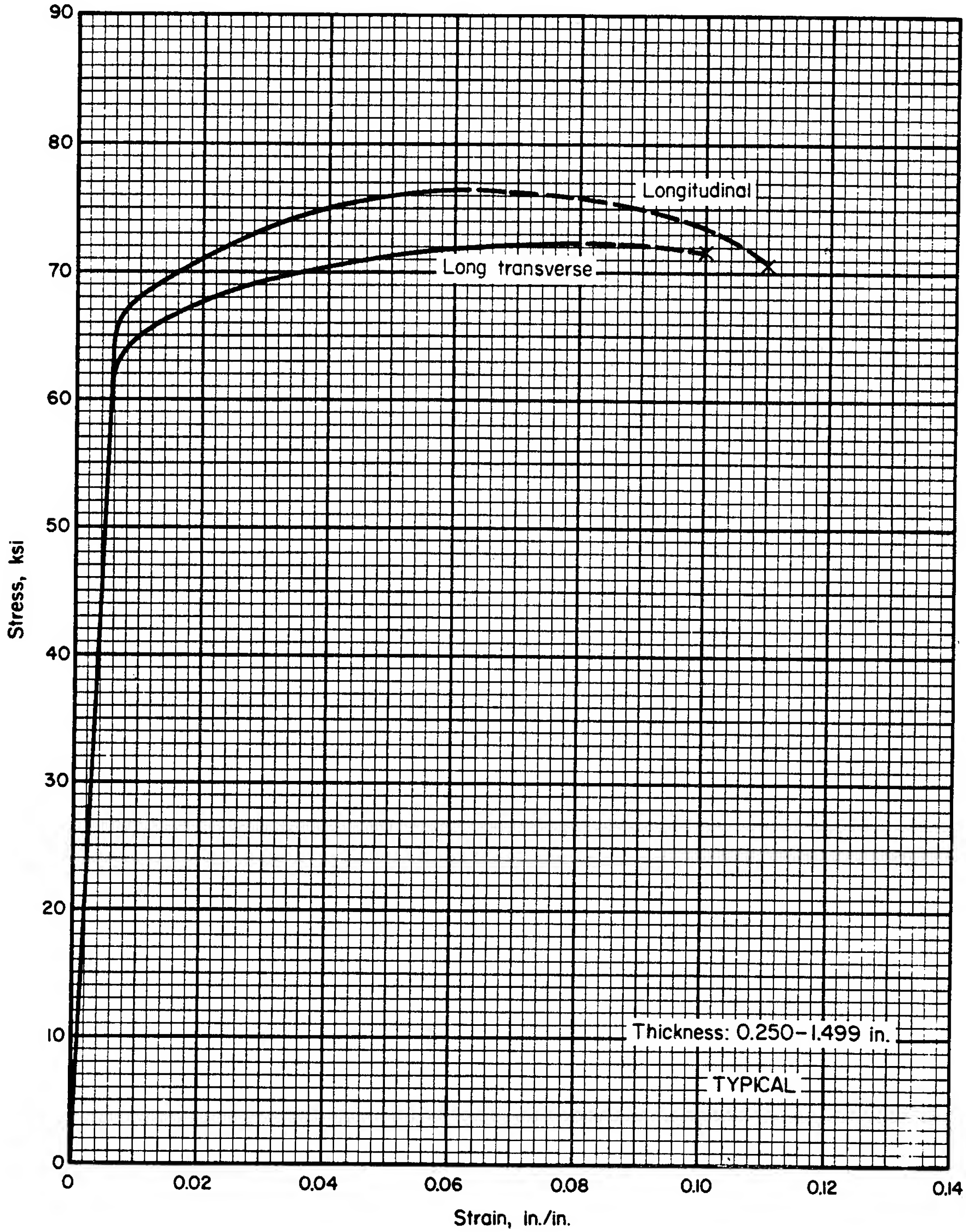

FIGURE 3.7.4.2.6(f). *Typical tensile stress-strain curves (full range) for 7075-T73 aluminum alloy extrusion at room temperature.*

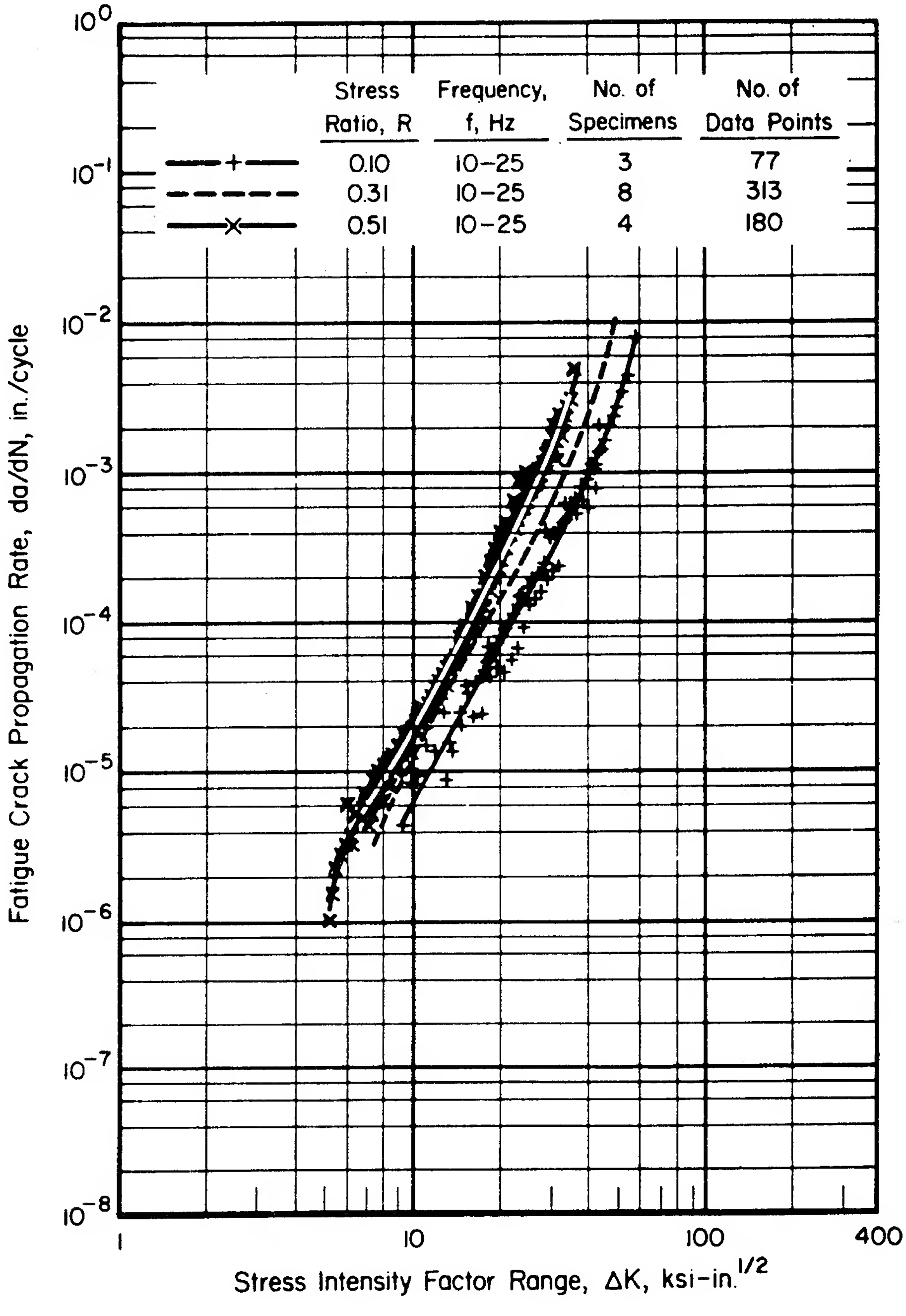

FIGURE 3.7.4.2.9(a). *Fatigue-crack-propagation data for 0.250-inch-thick, 7075-T7351 aluminum alloy plate with buckling restraint.* [*References 3.2.5.1.9(d) and 3.7.4.2.9(a)*].

Specimen Thickness:	*0.250 inch*	***Environment:***	***50% R. H.***
Specimen Width:	*8, 16, 36 inches*	***Temperature:***	***RT***
Specimen Type:	*CC*	***Orientation:***	***L-T***

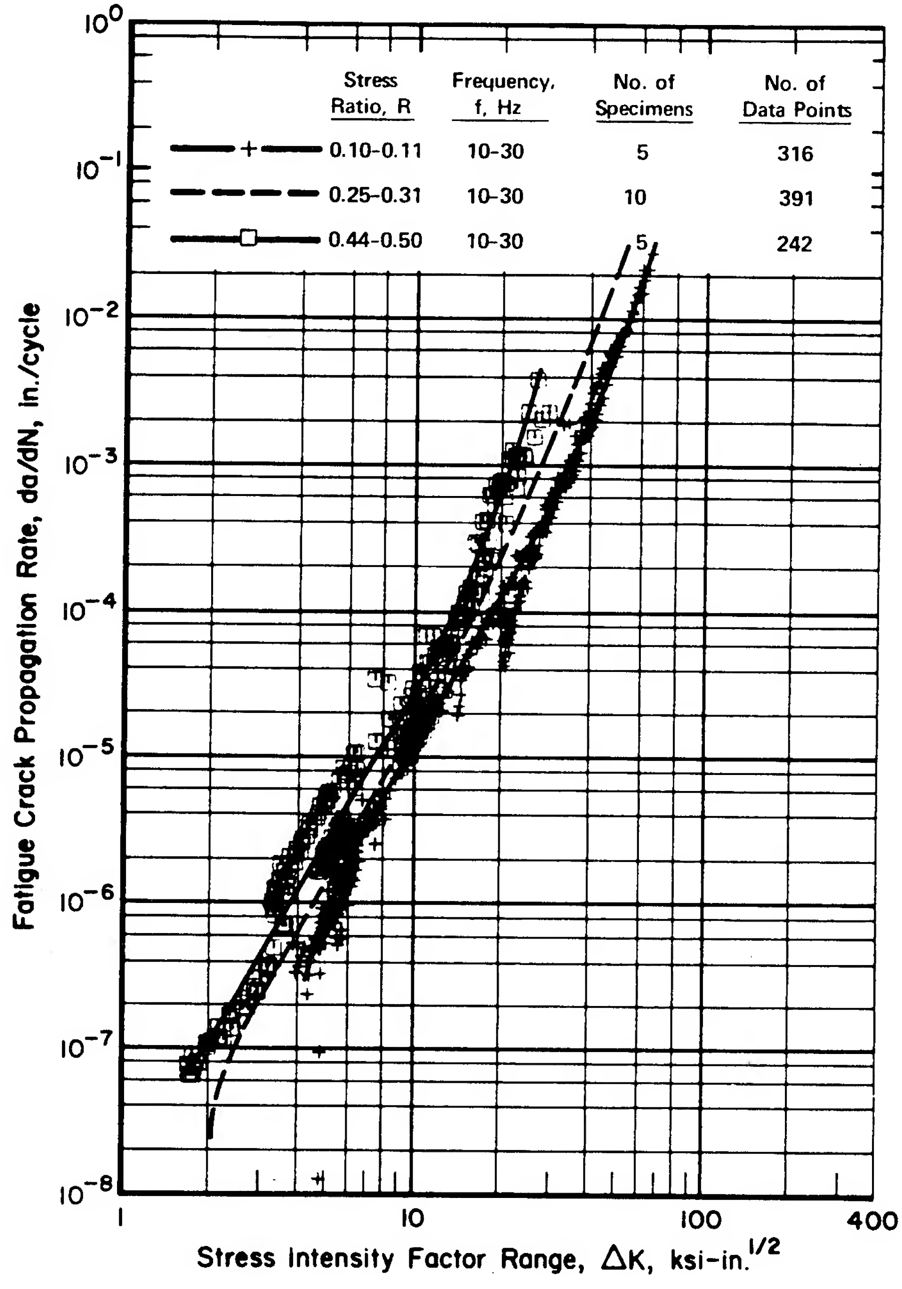

FIGURE 3.7.4.2.9(b). *Fatigue-crack-propagation data for 0.500-inch-thick 7075-T7351 aluminum alloy plate with buckling restraint. [References 3.1.2.1.6(j), 3.7.4.2.9(a) through (c)].*

Specimen Thickness:	*0.475-0.500 inch*	***Environment:***	***50-95% R.H.***
Specimen Width:	*6, 8, 16, 36 inches*	***Temperature:***	***RT***
Specimen Type:	*CC*	***Orientation:***	***L-T***

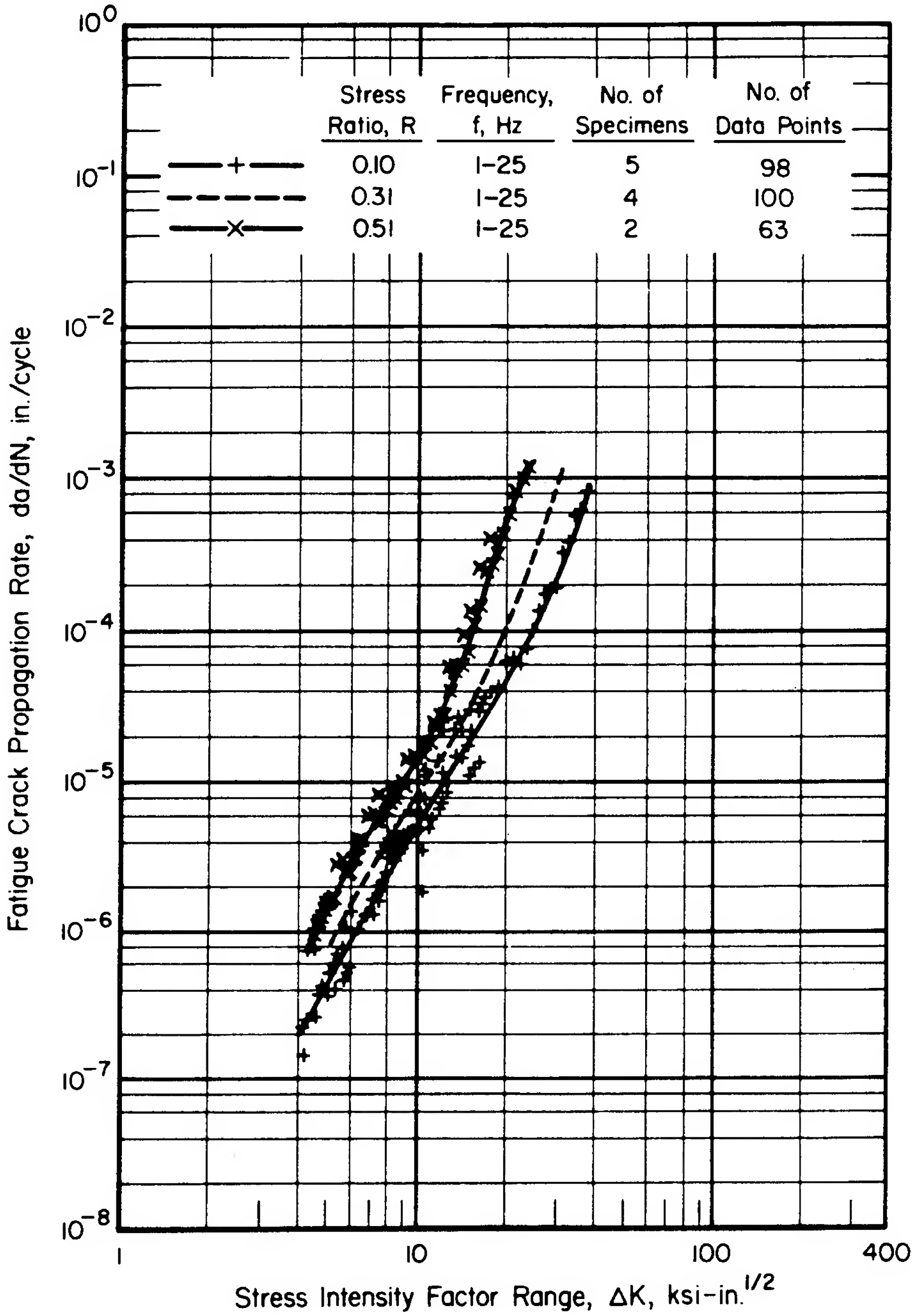

FIGURE 3.7.4.2.9(c). *Fatigue-crack-propagation data for 1.00-inch-thick 7075-T7351 aluminum alloy plate without buckling restraint. [References 3.2.5.1.9(d) and 3.7.4.2.9(a) and (b)].*

Specimen Thickness:	*1.00 inch*	***Environment:***	***50% R. H.***
Specimen Width:	*6, 8, 16, 36 inches*	***Temperature:***	***RT***
Specimen Type:	*CC, CT*	***Orientation:***	***L-T***

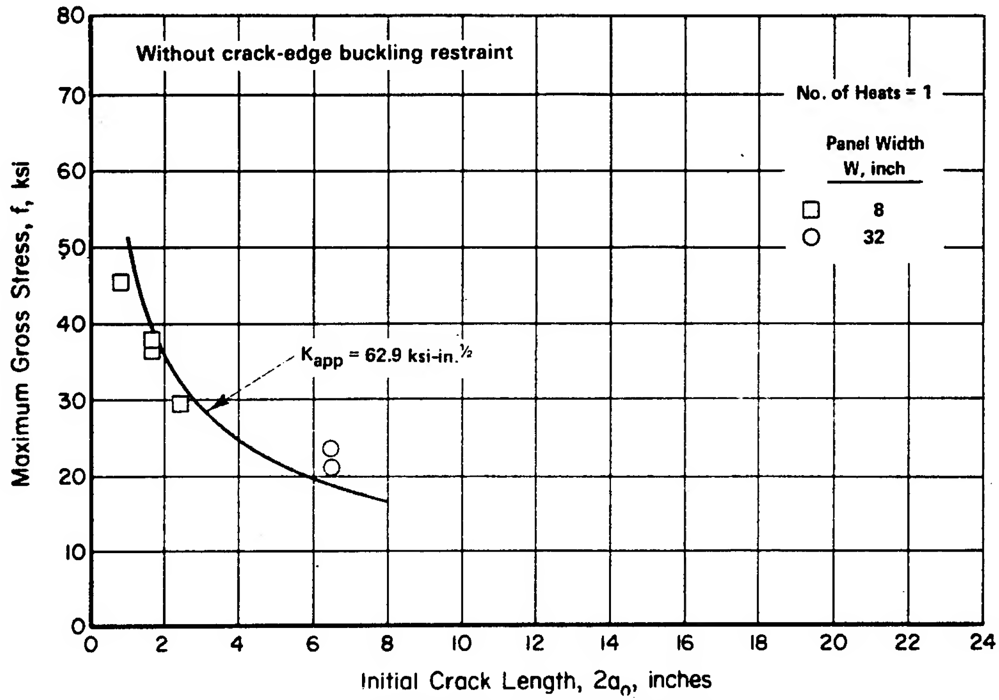

FIGURE 3.7.4.2.10(a). *Residual strength behavior of 0.600-inch-thick 7075-T7351 aluminum alloy plate at room temperature. Crack orientation is L-T.* [*Reference 3.1.2.1.6(g)*].

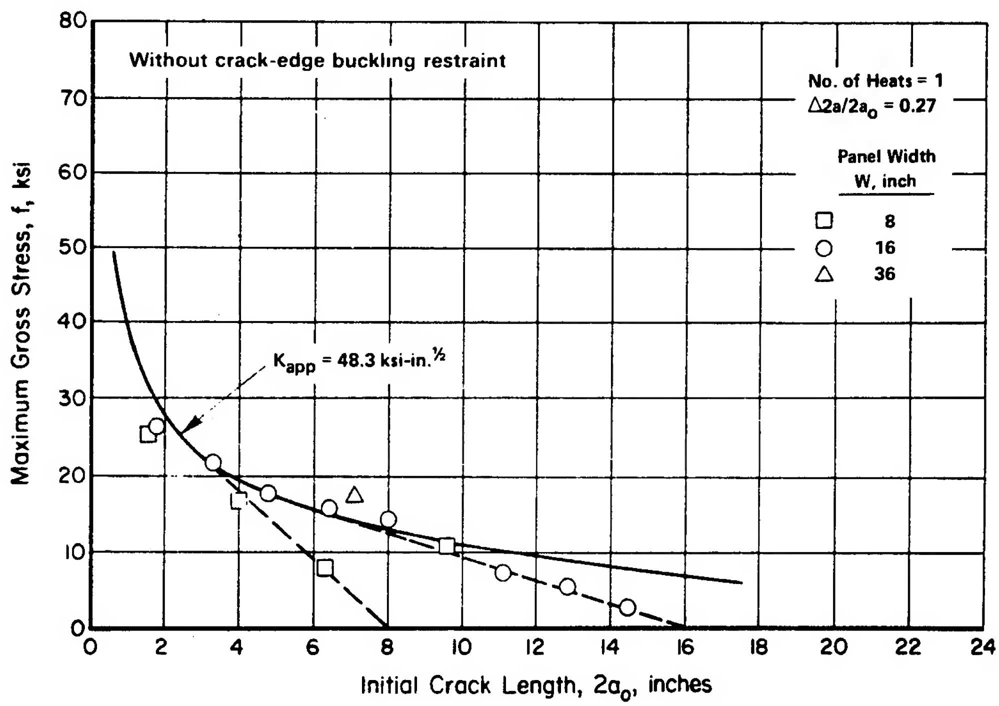

FIGURE 3.7.4.2.10(b). *Residual strength behavior of 1.00-inch-thick 7075-T7351 aluminum alloy plate at room temperature. Crack orientation is L-T.* [*Reference 3.1.2.1.6(j)*].

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3.7.5 7150 ALLOY

3.7.5.0 *Comments and Properties.*—7150, a second-generation version of 7050, is an Al-Zn-Mg-Cu-Zr alloy developed to provide higher strength properties than 7050 in thicknesses through 3 inches. 7150 is available in the form of plate and extrusion. The T61-type temper provides high strength with guaranteed levels of fracture toughness for plate. The T77-type temper provides high strength with guaranteed toughness and corrosion resistance. The T77-type temper has exfoliation and stress-corrosion rsistance comparable to the T76-type temper of the other 7000 series aluminum alloys. Refer to Section 3.1.2.3 for further comments regarding resistance of the alloy to stress-corrosion cracking.

Refer to Section 3.1.3.4 for comments regarding the weldability of the alloy.

Material specifications for 7150 are shown in Table 3.7.5.0(a). Room-temperature mechanical properties are presented in Tables 3.7.7.0(b_1) through (c_2).

Table 3.7.5.0(a). *Material Specifications for 7150 Aluminum Alloy*

Specification	Form
AMS 4306 (T6151)	Bare plate
AMS 4252 (T7751)	Bare plate
AMS 4307 (T61511)	Extrusion
AMS 4345 (T77511)	Extrusion

The temper index for 7150 is as follows:

Section	Temper
3.7.5.1	T6151 and T61511
3.7.5.2	T7751 and T77511

3.7.5.1 *T6151 and T61511 Tempers.*—Figures 3.7.5.1.6(a) and (b) present stress-strain and tangent-modulus curves for bare plate. Figures 3.7.5.1.6(c) and (d) depict stress-strain and tangent-modulus curves for extrusion.

3.7.5.2 *T7751 and T77511 Tempers.*—Figures 3.7.5.2.6(a) and (b) present stress-strain and tangent-modulus curves for bare plate. Figures 3.7.5.2.6(c) and (d) depict stress-strain and tangent-modulus curves for extrusion.

TABLE 3.7.5.0(b_1). *Design Mechanical and Physical Properties of 7150 Plate*

Specification	AMS 4306			
Form	Plate			
Temper	T6151			
Thickness, in.	0.750-1.000		1.001-1.500	
Basis	A	B	A	B
Mechanical Properties:				
F_{tu}, ksi:				
L	84[b]	87	84[c]	87
LT	84	87	84[d]	86
F_{ty}, ksi:				
L	78[b]	81	78[c]	81
LT	77	79	77	78
F_{cy}, ksi:				
L	77	80	75	77
LT	81	83	80	82
F_{su}, ksi	45	47	45	46
F_{bru}[a], ksi:				
(e/D = 1.5)	121	125	121	124
(e/D = 2.0)	155	160	155	158
F_{bry}[a], ksi:				
(e/D = 1.5)	102	105	101	104
(e/D = 2.0)	119	122	118	121
e, percent (S-basis):				
L	9	...	9	...
LT	9	...	9	...
E, 10^3 ksi	10.2			
E_c, 10^3 ksi	10.6			
G, 10^3 ksi	3.9			
μ	0.33			
Physical Properties:				
ω, lb/in.^{3}	0.102			
C, Btu/(lb)(F)	...			

[a] Bearing values are "dry pin" values per Section 1.4.7.1 See Table 3.1.2.1.1
[b] S basis. The A values are higher than specification minimum values as follows: F_{tu}(L) = 85 ksi and F_{ty}(L) = 79 ksi.
[c] S basis. The A values are higher than specification minimum values as follows: F_{tu}(L) = 86 ksi and F_{ty}(L) = 80 ksi.
[d] S basis. The A value is higher than specification minimum values as follows: F_{tu}(LT) = 85 ksi.

TABLE 3.7.5.0(b_2). *Design Mechanical and Physical Properties of 7150 Plate—Continued*

Specification	AMS 4252			
Form	Plate			
Temper	T7751			
Thickness, in.	0.250-0.499	0.500-0.749	0.750-1.500	1.501-3.000
Basis	S	S	S	S
Mechanical Properties:				
F_{tu}, ksi:				
L	80	83	84	82
LT	80	83	84	82
ST	...	...	...	77
F_{ty}, ksi:				
L	74	77	78	76
LT	74	76	77	75
ST	...	...	...	67
F_{cy}, ksi:				
L	73	76	77	75
LT	77	79	81	79
F_{su}, ksi	46	47	48	47
F_{bru}[a], ksi:				
(e/D = 1.5)	119	124	125	122
(e/D = 2.0)	154	160	162	158
F_{bry}[a], ksi:				
(e/D = 1.5)	102	105	106	104
(e/D = 2.0)	177	120	121	118
e, percent:				
L	8	8	8	7
LT	8	8	8	6
ST	...	...	...	1
E, 10^3 ksi	10.3			
E_c, 10^3 ksi	10.7			
G, 10^3 ksi	3.9			
μ	0.33			
Physical Properties:				
ω, lb./in.^{3}	0.102			
C, K, and α	...			

[a]Bearing values are "dry pin" values per Section 1.4.7.1. See Table 3.1.2.1.1.

TABLE 3.7.5.0(c$_1$). *Design Mechanical and Physical Properties of 7150 Aluminum Alloy Extrusion*

Specification	AMS 4307					
Form	Extrusion					
Temper	T61511					
Thickness or diameter, in.	0.250-0.499	0.500-0.749	0.750-0.999	1.000-1.499		1.500-2.000
Basis	S	S	S	A	B	S
Mechanical Properties:						
F_{tu}, ksi:						
L	87	88	89	89	94	89
LT	80	79	79	85	86	74
F_{ty}, ksi:						
L	82	83	84	83	88	84
LT	73	73	73	77	78	68
F_{cy}, ksi:						
L	80	81	82	82	87	84
LT	80	80	80	77	81	75
F_{su}, ksi	44	45	45	44	46	42
F_{bru}[a], ksi:						
(e/D = 1.5)	118	120	120	118	125	116
(e/D = 2.0)	152	153	154	152	161	150
F_{bry}[a], ksi:						
(e/D = 1.5)	100	100	100	96	102	94
(e/D = 2.0)	118	120	120	117	124	117
e, percent (S-basis):						
L	8	9	8	8	...	8
E, 10^3 ksi	10.4					
E_c, 10^3 ksi	11.0					
G, 10^3 ksi	4.0					
μ	0.33					
Physical Properties:						
ω, lb/in.^{3}	0.102					
C, K, and α	...					

[a]Bearing values are "dry pin" values per Section 1.4.7.1.

TABLE 3.7.5.0(c_2). *Design Mechanical and Physical Properties of 7150 Aluminum Alloy Extrusion—Continued*

Specification	AMS 4345			
Form	Extrusion			
Temper	T77511			
Cross-sectional area, in^2	≤20			
Thickness or diameter, in.	≤0.249	0.250-0.499	0.500-0.749	0.750-2.000
Basis	S	S	S	S
Mechanical Properties:				
F_{tu}, ksi:				
L	85	87	88	89
LT	81	82	83	83
F_{ty}, ksi:				
L	78	82	83	84
LT	74	76	79	78
F_{cy}, ksi:				
L	78	82	83	85
LT	76	80	81	82
F_{su}, ksi	44	45	46	46
F_{bru}[a], ksi:				
(e/D = 1.5)	122	124	125	123
(e/D = 2.0)	158	161	162	159
F_{bry}[a], ksi:				
(e/D = 1.5)	100	105	106	108
(e/D = 2.0)	118	124	125	127
e, percent:				
L	7	8	9	8
E, 10^3 ksi	10.4			
E_c, 10^3 ksi	10.9			
G, 10^3 ksi	4.0			
μ	0.33			
Physical Properties:				
ω, lb/in.^{3}	0.102			
C, K, and α	...			

[a]Bearing values are "dry pin" values per Section 1.4.7.1.

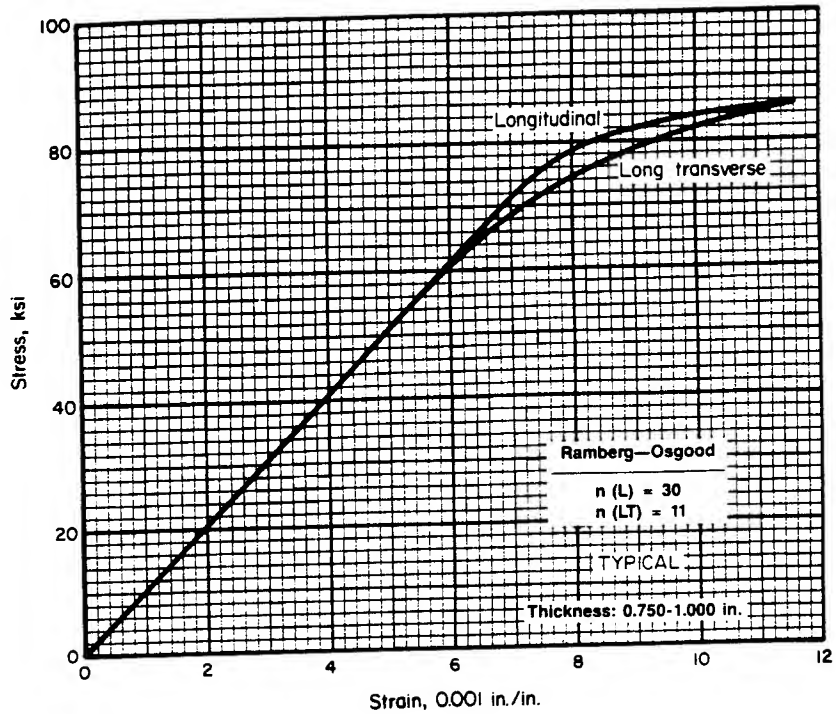

FIGURE 3.7.5.1.6(a). *Typical tensile stress-strain curves for 7150-T6151 aluminum alloy plate at room temperature.*

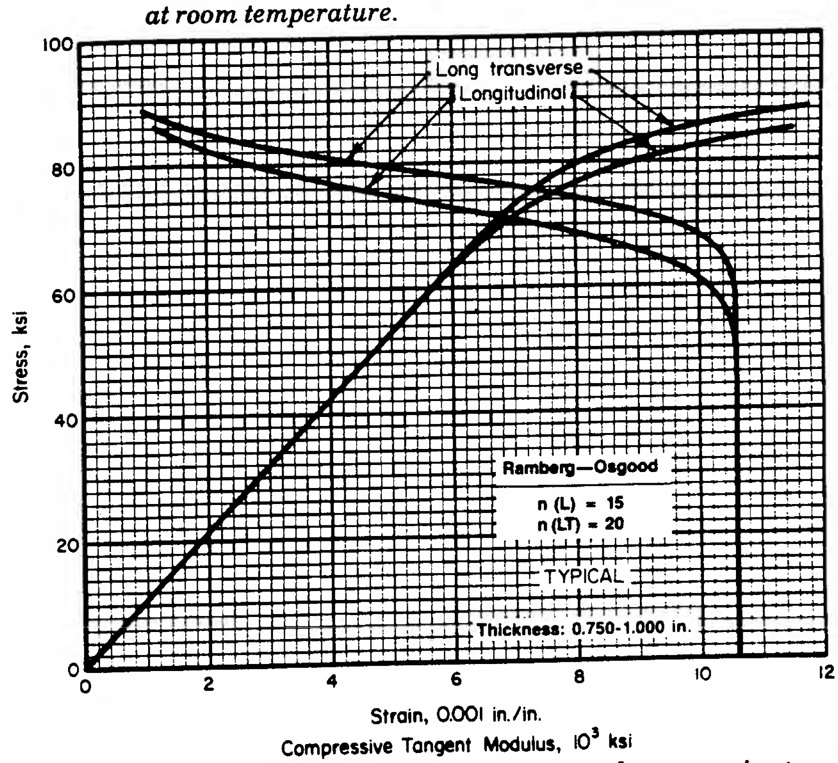

FIGURE 3.7.5.1.6(b). *Typical compressive stress-strain and compressive tangent-modulus curves for 7150-T6151 aluminum alloy plate at room temperature.*

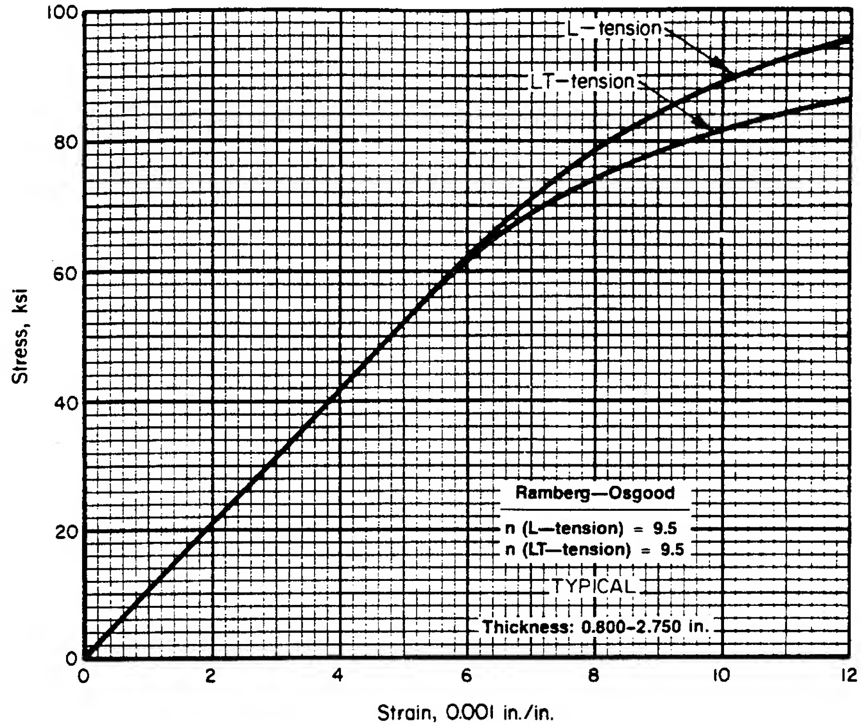

FIGURE 3.7.5.1.6(c). *Typical tensile stress-strain curves for 7150-T61511 aluminum alloy extrusion at room temperature.*

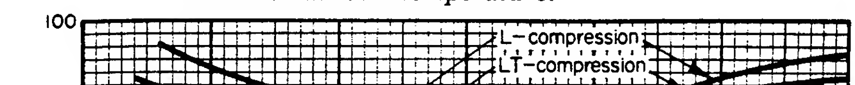

FIGURE 3.7.5.1.6(d). *Typical compressive stress-strain and compressive tangent-modulus curves for 7150-T61511 aluminum alloy extrusion at room temperature.*

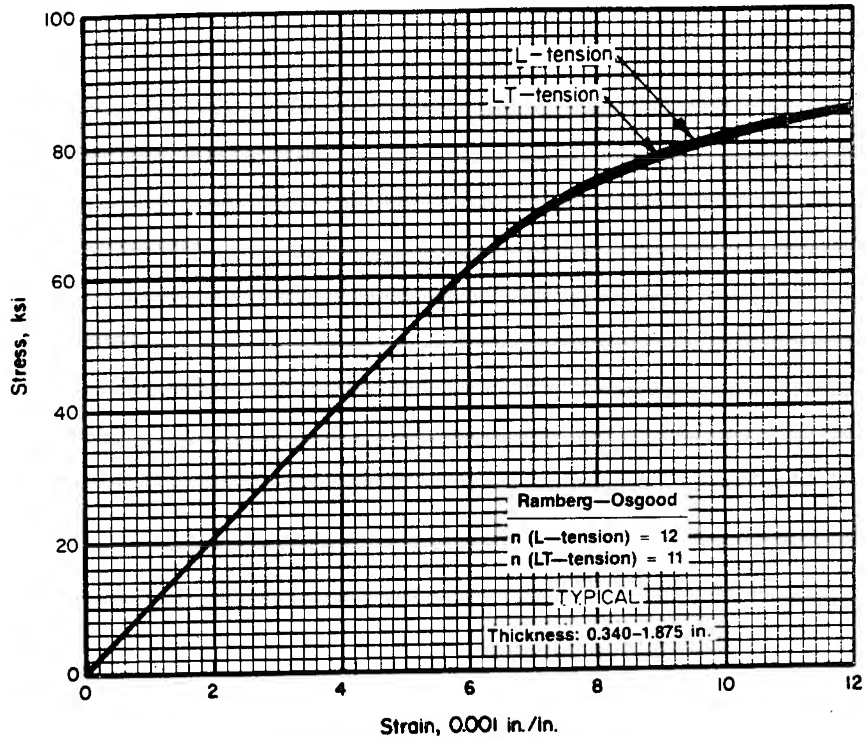

FIGURE 3.7.5.2.6(a). *Typical tensile stress-strain curves for 7150-T7751 aluminum alloy plate at room tempearture.*

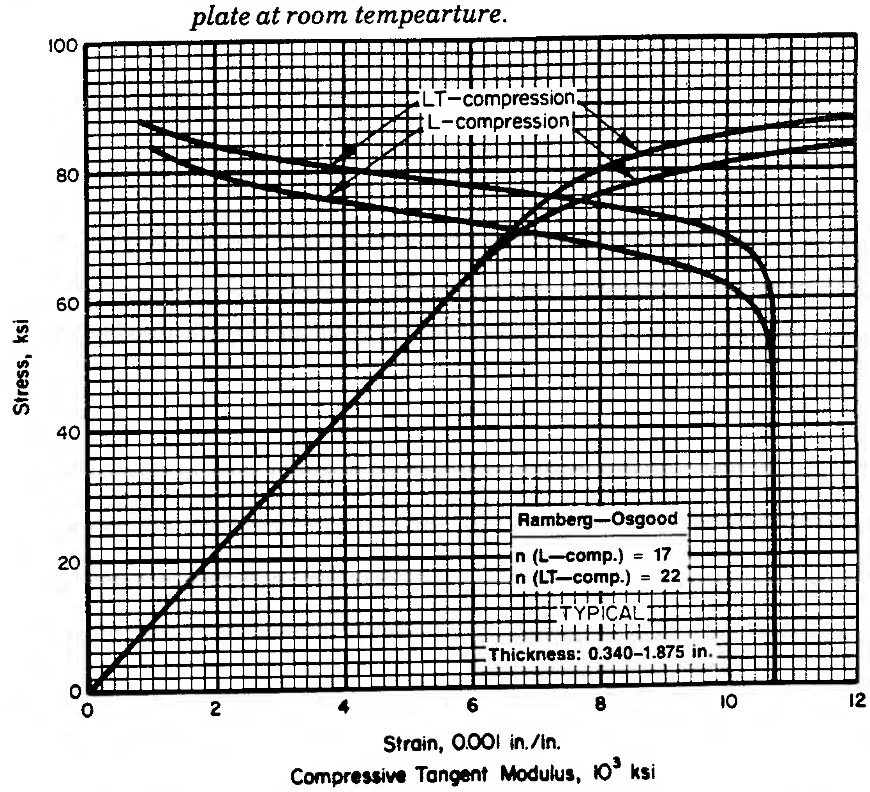

FIGURE 3.7.5.2.6(b). *Typical compressive stress-strain and tangent-modulus curves for 7150-T7751 aluminum alloy plate at room temperature.*

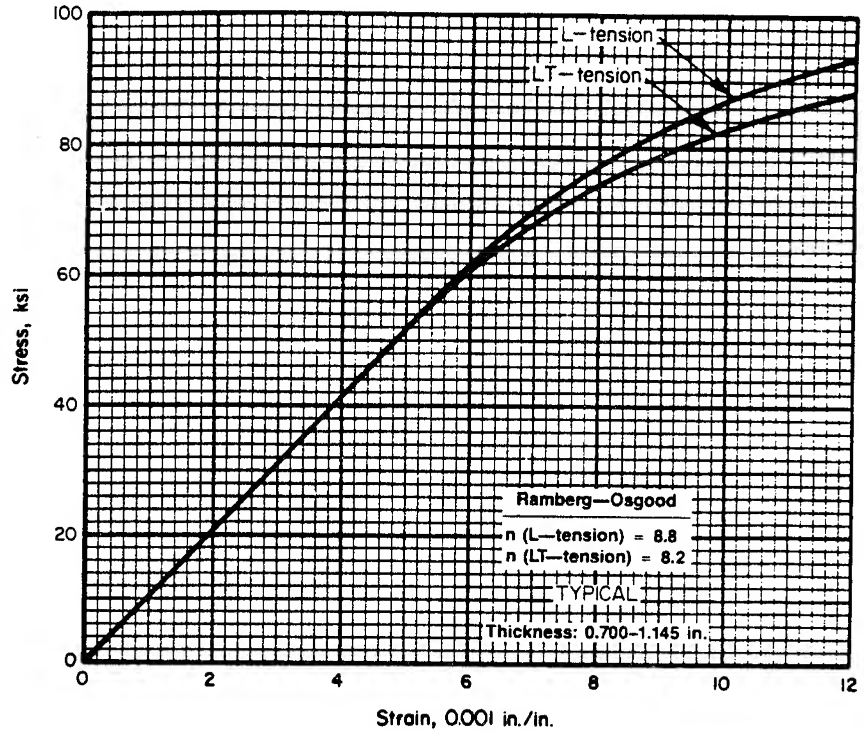

FIGURE 3.7.5.2.6(c). *Typical tensile stress-strain curves for 7150-T77511 aluminum alloy extrusion at room tempearture.*

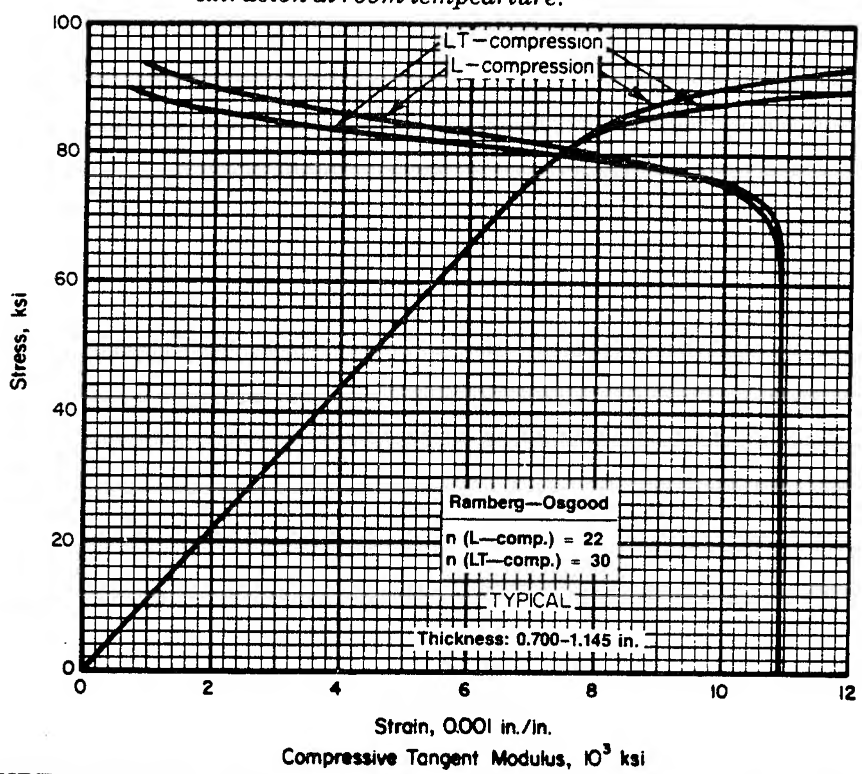

FIGURE 3.7.5.2.6(d). *Typical compressive stress-strain and tangent-modulus curves for 7150-T77511 aluminum alloy extrusion.*

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3.7.6 7175 Alloy

3.7.6.0 *Comments and Properties.*—7175 is a high-purity, high-strength Al-Zn-Mg-Cu alloy. In the form of die forgings the alloy is available in the T66, T74, and T7452 tempers. Die forgings of 7175-T66 develop higher static strength than 7075-T6 forgings with fatigue, fracture, and stress-corrosion properties about equivalent to those of 7075-T6 forgings. 7175-T74-type die and hand forgings develop static strengths about equivalent to those of 7075-T6 forgings, with toughness and fatigue properties equal or superior to those of 7075-T73 forgings. The T74-type temper provides stress-corrosion resistance and strength characteristics intermediate to those of T76 and T73 in 7075. Refer for Section 3.1.2.3 for comments regarding the resistance of the alloy to stress-corrosion cracking, and to Section 3.1.3.4 for comments regarding the weldability of the alloy.

Material specifications for 7175 are presented in Table 3.7.6.0(a). Room-temperature mechanical and physical properties are shown in Tables 3.7.6.0(b) through (d).

TABLE 3.7.6.0(a). *Material Specifications for 7175 Aluminum Alloy*

Specification	Form
AMS 4148 (T66)	Die forging
AMS 4149 (T74)	Die and hand forging
AMS 4179 (T7452)	Hand forging
MIL-A-22771	Forging
AMS 4344 (T73511)	Extrusion

The temper index for 7175 is as follows:

Section	Temper
3.7.6.1	T73511
3.7.6.2	T74 and T7452 (formerly T736, T73652)

3.7.6.1 *T73511 Temper.*—Figures 3.7.6.1.6(a) and (b) show tensile and compressive stress-strain and tangent-modulus curves for extrusion. Figures 3.7.6.1.8(a) through (d) present fatigue curves for extrusion.

3.7.6.2 *T74 and T7452 Tempers.*—Figures 3.7.6.2.6(a) through (f) present tensile and compressive stress-strain and tangent-modulus curves for die and hand forging. Figures 3.7.6.2.8(a) and (b) present fatigue curves for die and hand forging.

TABLE 3.7.6.0(b). *Design Mechanical and Physical Properties of 7175 Aluminum Alloy Die Forging*

Specification	AMS 4148	AMS 4149						
Form	Die forging							
Temper	T66	T74[a,b]						
Thickness, in.	≤3.000	<1.000	1.001-2.000		2.001-3.000	3.001-4.000	4.001-5.000	5.001-6.000
Basis	S	S	A	B	S	S	S	S
Mechanical Properties:								
F_{tu}, ksi:								
L	86	76	74	77	76	73	70	68
T[c]	77	71	71[d]	...	71	70	68	65
F_{ty}, ksi:								
L	76	66	64	67	66	63	61	58
T[c]	66	62	62[d]	...	62	60	58	55
F_{cy}, ksi:								
L	...	67	65	68	67	...	...	...
ST	...	63	61	64	63	...	...	...
F_{su}, ksi	...	43	42	44	43	...	...	...
F_{bru}[e], ksi:								
(e/D = 1.5)	...	106	105	109	106	...	...	...
(e/D = 2.0)	...	140	137	142	140	...	...	...
F_{bry}[e], ksi:								
(e/D = 1.5)	...	86	84	88	86	...	...	...
(e/D = 2.0)	...	102	99	103	102	...	...	...
e, percent (S-basis):								
L	7	7	7	...	7	7	7	7
T[c]	4	4	4	...	4	4	4	4
E, 10^3 ksi	10.2							
E_c, 10^3 ksi	10.7							
G, 10^3 ksi	3.9							
μ	0.33							
Physical Properties:								
ω, lb/in.^{3}	0.101							
C, Btu/(lb)(F)	0.23 (at 212 F)							
K, Btu/[(hr)(ft^2)(F)/ft]	76 (at 77 F for T66); 90 (at 77 F for T736)							
α, 10^{-6} in./in./F	12.9 (68 to 212 F)							

a When die forgings are machined before heat treatment, section thickness at time of heat treatment shall determine minimum mechanical properties as long as original (as-forged) thickness does not exceed maximum thickness for the alloy as shown in the table.
b Design allowables were based upon data obtained from testing die forgings, heat treated by suppliers, and supplied in T74 temper.
c For die forgings, T indicates any grain direction not within ±15° of being parallel to the forging flow lines. Specimens to test transverse properties should be located as close to the short transverse direction as possible.
d Specification value. T tensile properties are presented on an S basis only.
e Bearing values are "dry pin" values per Section 1.4.7.1.

TABLE 3.7.6.0(c_1). *Design Mechanical and Physical Properties of 7175 Aluminum Alloy Hand Forging*

Specification	AMS 4149 and MIL-A-22771				
Form	Hand forging				
Temper	T74				
Thickness or diameter[a,b], in.	1.001-2.000	2.001-3.000	3.001-4.000	4.001-5.000	5.001-6.000
Basis	S	S	S	S	S
Mechanical Properties:					
F_{tu}, ksi:					
L	73	73	71	68	65
LT	71	71	70	67	64
ST	...	69	68	66	63
F_{ty}, ksi:					
L	63	63	61	57	54
LT	60	60	58	56	52
ST	...	60	57	55	52
F_{cy}, ksi:					
L	63	63	61	59	55
LT	62	63	61	60	56
ST	61	62	60	59	55
F_{su}, ksi:					
L	43	43	43	41	39
LT	42	42	41	39	38
ST	42	42	41	39	38
F_{bru}[c], ksi:					
(e/D = 1.5)	106	106	104	100	95
(e/D = 2.0)	138	138	136	131	125
F_{bry}[c], ksi:					
(e/D = 1.5)	73	78	80	81	76
(e/D = 2.0)	89	94	95	95	90
e, percent:					
L	9	9	9	8	8
LT	5	5	5	5	5
ST	...	4	4	4	4
E, 10^3 ksi	10.2				
E_c, 10^3 ksi	10.6				
G, 10^3 ksi	3.9				
μ	0.33				
Physical Properties:					
ω, lb/in.^{3}	0.101				
C, Btu/(lb)(F)	0.23 (at 212 F)				
K, Btu/[(hr)(ft^2)(F)/ft]	90 (at 77 F)				
α 10^{-6} in./in./F	12.9 (68 to 212 F)				

[a]When hand forgings are machined before heat treatment, the section thickness at time of heat treatment shall determine the minimum mechanical properties as long as the original (as-forged) thickness does not exceed the maximum thickness for the alloy as shown in the table.
[b]The maximum cross-sectional area of hand forgings in 256 sq.in.
[c]Bearing values are "dry pin" values per Section 1.4.7.1.

TABLE 3.7.6.0(c_2). *Design Mechanical and Physical Properties of 7175 Aluminum Alloy Hand Forging—Continued*

Specification	AMS 4149 and MIL-A-22771				
Form	Hand forging				
Temper	T7452				
Thickness or diameter[a], in.	1.001-2.000	2.001-3.000	3.001-4.000	4.001-5.000	5.001-6.000
Basis	S	S	S	S	S
Mechanical Properties:					
F_{tu}, ksi:					
L	71	71	68	65	63
LT	69	69	67	64	61
ST	...	67	65	63	60
F_{ty}, ksi:					
L	61	61	57	54	51
LT	58	58	55	52	49
ST	...	54	51	49	46
F_{cy}, ksi:					
L	58	58	55	52	49
LT	61	61	57	54	50
ST	60	60	57	54	51
F_{su}, ksi:					
L	38	39	39	38	37
LT	38	39	38	38	36
ST	40	41	40	39	38
F_{bru}[b], ksi:					
(e/D = 1.5)	102	102	99	95	90
(e/D = 2.0)	133	133	130	124	118
F_{bry}[b], ksi:					
(e/D = 1.5)	80	82	80	76	72
(e/D = 2.0)	95	98	95	92	87
e, percent:					
L	9	9	9	8	8
LT	5	5	5	5	5
ST	...	4	4	4	4
E, 10^3 ksi	10.2				
E_c, 10^3 ksi	10.5				
G, 10^3 ksi	3.9				
μ	0.33				
Physical Properties:					
ω, lb/in.^{3}	0.101				
C, Btu/(lb)(F)	0.23 (at 212 F)				
K, Btu/[(hr)(ft^2)(F)/ft]	90 (AT 77 F)				
α 10^{-6} in./in./F	12.9 (68 to 212 F)				

[a]The maximum cross-sectional area of hand forgings is 256 sq.in.
[b]Bearing values are "dry pin" values per Section 1.4.7.1.

TABLE 3.7.6.0(d). *Design Mechanical and Physical Properties of 7175 Aluminum Alloy Extrusion*

Specification	AMS 4344	
Form	Extrusion	
Condition	T73511	
Cross-sectional area, in^2	32-65	
Thickness or diameter, in.	0.250-0.999	1.000-2.000
Basis	S	S
Mechanical Properties:		
F_{tu}, ksi:		
L	69	69
LT	63	63
F_{ty}, ksi:		
L	59	59
LT	52	52
F_{cy}, ksi:		
L	...	59
LT	...	59
F_{su}, ksi	...	40
F_{bru}[a], ksi:		
(e/D = 1.5)	...	97
(e/D = 2.0)	...	125
F_{bry}[a], ksi:		
(e/D = 1.5)	...	79
(e/D = 2.0)	...	95
e, percent:		
L	...	8
LT	...	4
E, 10^3 ksi	10.1	
E_c, 10^3 ksi	10.5	
G, 10^3 ksi	3.9	
μ	1.33	
Physical Properties:		
ω, lb/in.^{3}	0.101	
C, Btu/(lb)(F)	0.23 (at 212 F)	
K, Btu/[(hr)(ft^2)(F)/ft]	...	
α, 10^{-6} in./in./F	12.9 (68 to 212 F)	

[a]Bearing values are "dry pin" values per Section 1.4.7.1.

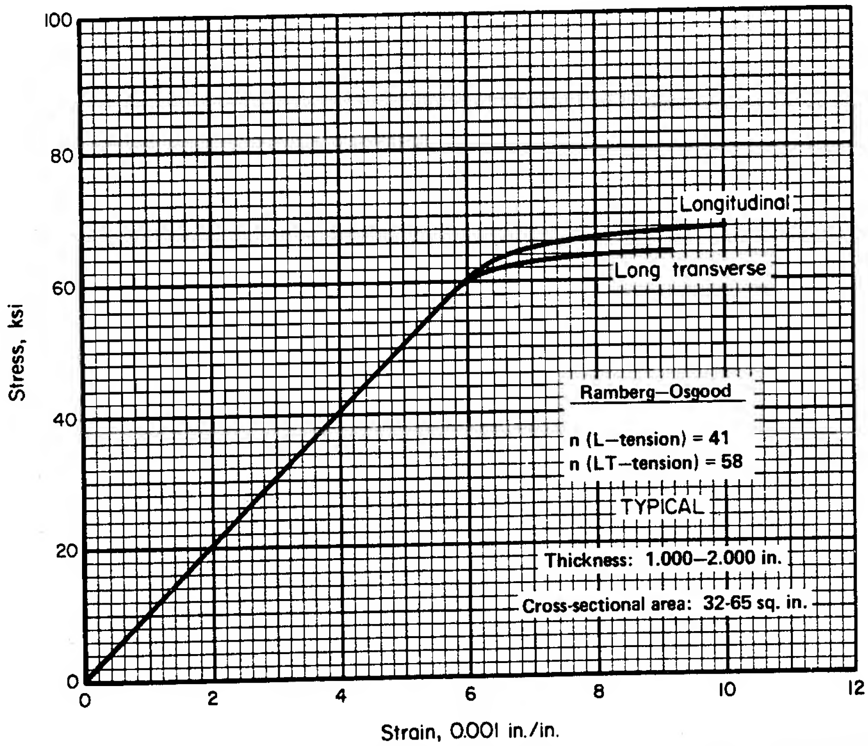

FIGURE 3.7.6.1.6(a). *Typical tensile stress-strain curves for aluminum alloy 7175-T73511 extrusion at room temperature.*

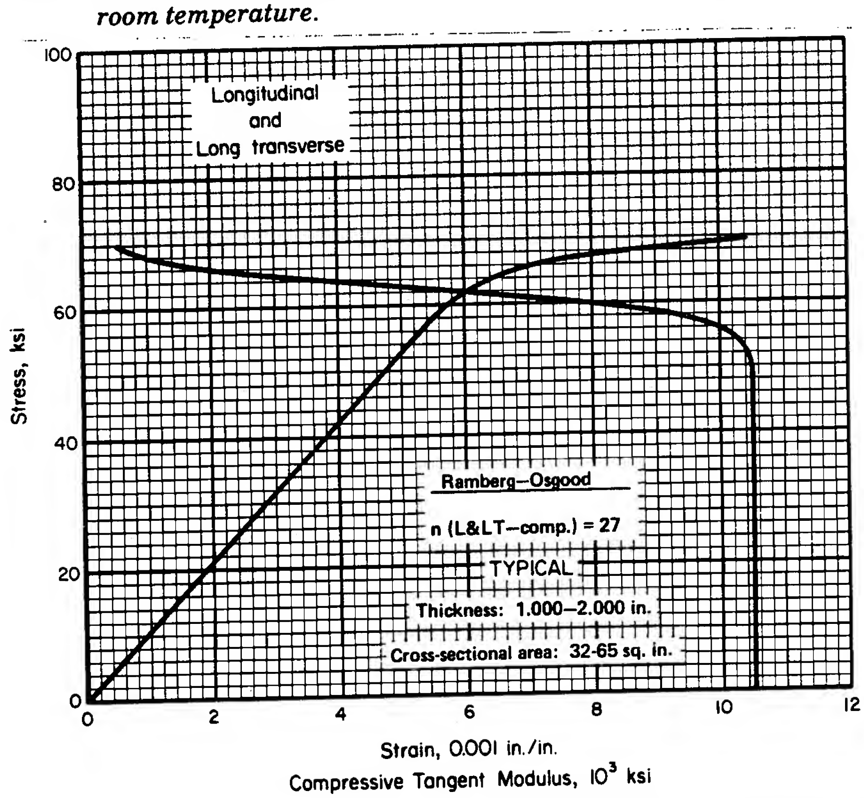

FIGURE 3.7.6.1.6(b). *Typical compressive stress-strain and tangent-modulus curves for aluminum alloy 7175-T73511 extrusion at room temperature.*

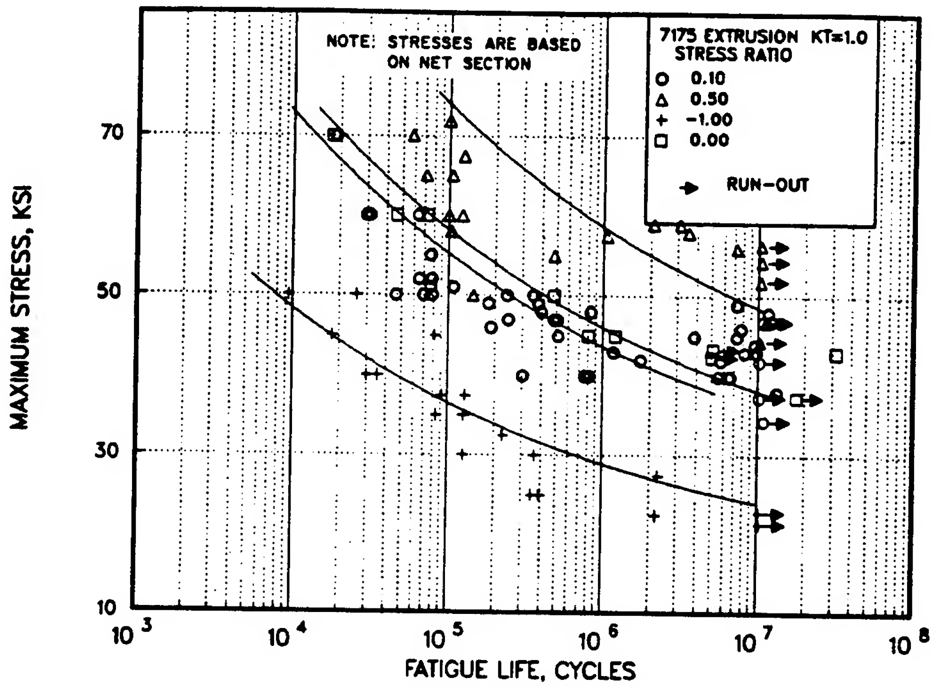

FIGURE 3.7.6.1.8(a). *Best-fit S/N curves for unnotched 7175-T73511 alloy extrusion, longitudinal direction.*

Correlative Information for Figure 3.7.6.1.8(a)

Product Form: Extrusion 1.8-inch thick, extruded round, 3-3/4-inch diameter, extruded rectangle, 2-1/2 × 5-inch thick, extrusion, unspecified size

Properties:

TUS, ksi	TYS, ksi	Temp., F
76	67	70

Specimen Details: 0.25-inch minimum diameter hourglass gage section 30-inch diameter

Surface Condition: 32 RMS gage section specified

References: 3.7.6.1.8(a), (b), and (c)

Test Parameters:
Loading - Axial
Frequency - Not specified
Temperature - 70 F
Environment - Air

No. of Heats/Lots: 11

Equivalent Stress Equation:
Log N_f = 12.01-5.26 log (S_{eq})
$S_{eq} = S_a + 0.32S_m - 15.04$
Standard Deviation in Log (Life) = 18.44 (1/S_{eq})
Adjusted R^2 = 58

Sample Size: 96

[Caution: The equivalent stress model may provide unrealistic life predictions for stress ratios beyond those represented above]

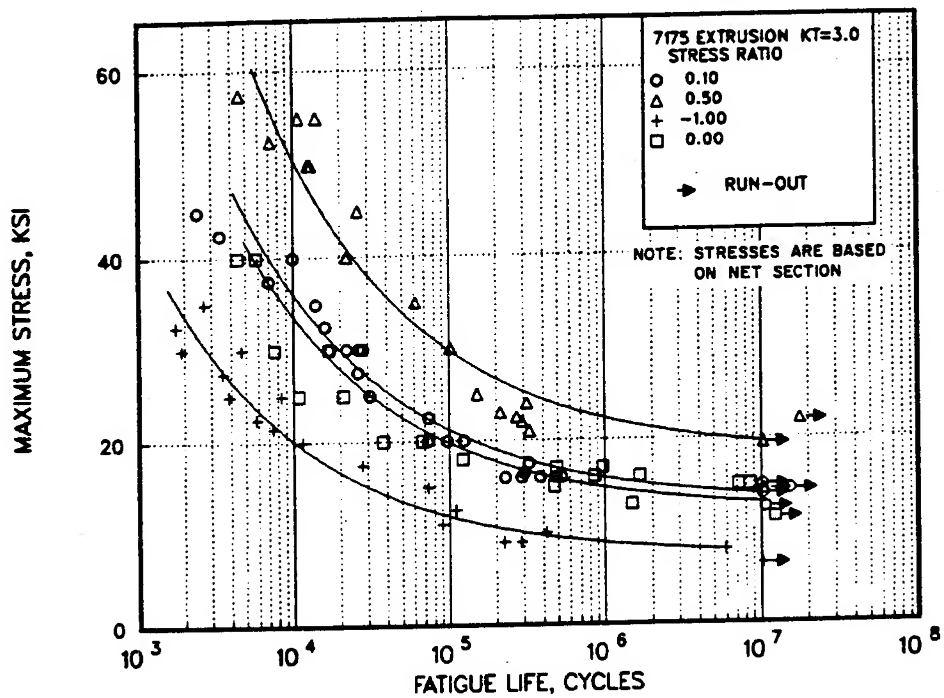

FIGURE 3.7.6.1.8(b). *Best-fit S/N curves for notched, K_t=3.0, 7175-T73511 alloy extrusion, longitudinal direction.*

Correlative Information for Figure 3.7.6.1.8(b)

Product Form: Extrusion 1.8-inch thick, extruded round, 3-3/4-inch diameter, extruded rectangle, 2-1/2 × 5-inch thick, extrusion, unspecified size

Properties:

TUS, ksi	TYS, ksi	Temp., F
76	67	70

Specimen Details: Circumferential notch,
K_t=3
0.5-inch gross diameter
0.36-inch net diameter
0.0005-inch notch radius
Circumferential 60° V notch

References: 3.7.6.1.8(a), (b), and (c)

Test Parameters:
Loading - Axial
Frequency - Not specified
Temperature - 70 F
Environment - Air

No. of Heats/Lots: 11

Equivalent Stress Equation:
$\text{Log } N_f = 6.50\text{-}2.25 \log (S_{eq})$
$S_{eq} = S_a + 0.20 S_m - 7.21$
Standard Deviation in Log (Life) = 3.92 ($1/S_{eq}$)
Adjusted R^2 = 91

Sample Size: 86

[Caution: The equivalent stress model may provide unrealistic life predictions for stress ratios beyond those represented above]

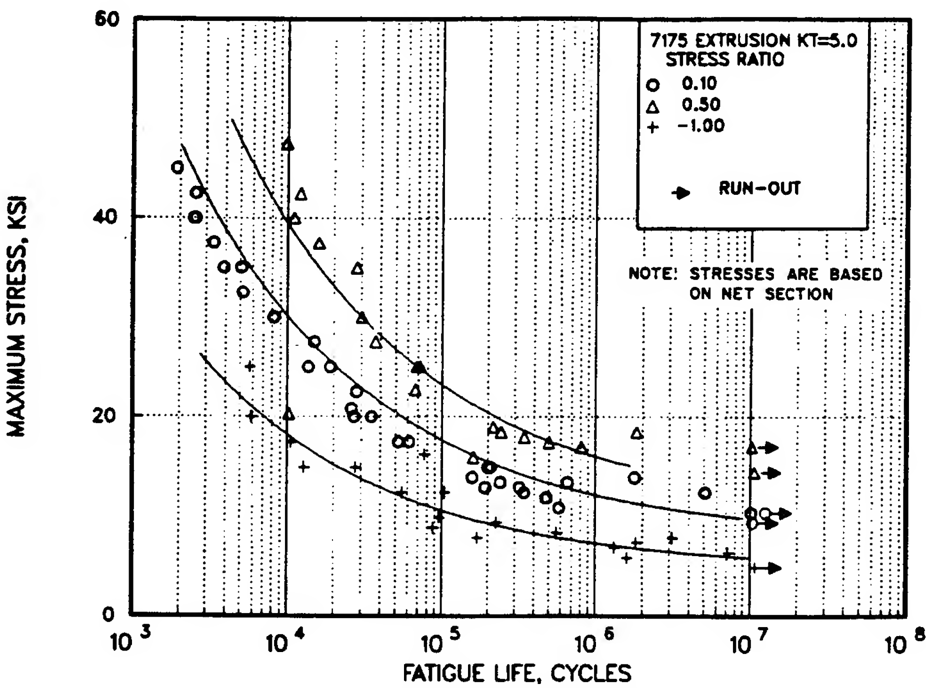

FIGURE 3.7.6.1.8(c). *Best-fit S/N curves for notched, K_t=5.0, 7175-T73511 alloy extrusion, longitudinal direction.*

Correlative Information for Figure 3.7.6.1.8(c)

Product Form: Extrusion, 1.8-inch thick

Properties:	TUS, ksi	TYS, ksi	Temp., F
	76	67	70

Specimen Details: Circumferential notch, K_t=5
0.5-inch gross diameter
0.36-inch net diameter
0.0005-inch notch radius

References: 3.7.6.1.8(a) and (b)

Test Parameters:
Loading - Axial
Frequency - Not specified
Temperature - 70 F
Environment - Air

No. of Heats/Lots: 10

Equivalent Stress Equation:
$\text{Log } N_f = 7.12\text{-}2.78 \log (S_{eq})$
$S_{eq} = S_a + 0.28\, S_m$
Standard Deviation in Log (Life) = 3.71 ($1/S_{eq}$)
Adjusted R^2 = 90

Sample Size: 136

[Caution: The equivalent stress model may provide unrealistic life predictions for stress ratios beyond those represented above]

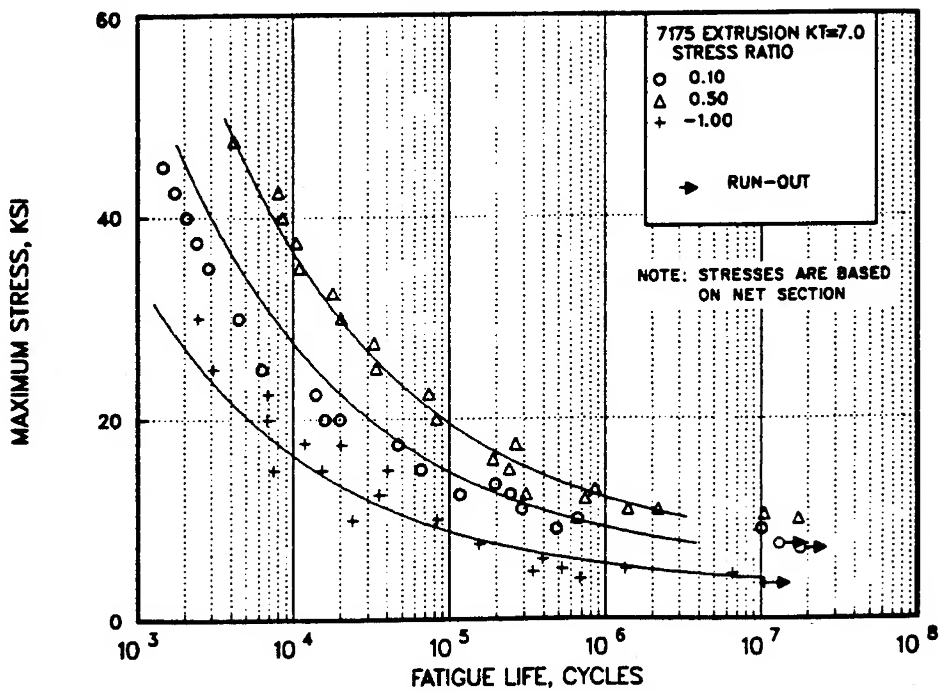

FIGURE 3.7.6.1.8(d). *Best-fit S/N curves for notched, K_t=7.0, 7175-T73511 alloy extrusion, longitudinal direction.*

Correlative Information for Figure 3.7.6.1.8(d)

Product Form: Extrusion, 1.8-inch thick

Properties:

TUS, ksi	TYS, ksi	Temp., F
76	67	70

Specimen Details: Circumferential notch, K_t=7
0.5-inch gross diameter
0.36-inch net diameter
0.0005-inch notch radius

References: 3.7.6.1.8(a) and (b)

Test Parameters:
Loading - Axial
Frequency - Not specified
Temperature - 70 F
Environment - Air

No. of Heats/Lots: 9

Equivalent Stress Equation:
$\text{Log } N_f = 7.15\text{-}2.78 \text{ Log } (S_{eq})$
$S_{eq} = S_a + 0.27\, S_m - 2.88$
Std. Deviation in Log(Life) = $0.11 + 1.60\ (1/S_{eq})$
Adjusted R^2 = 92

Sample Size: 63

[Caution: The equivalent stress model may provide unrealistic life predictions for stress ratios beyond those represented above]

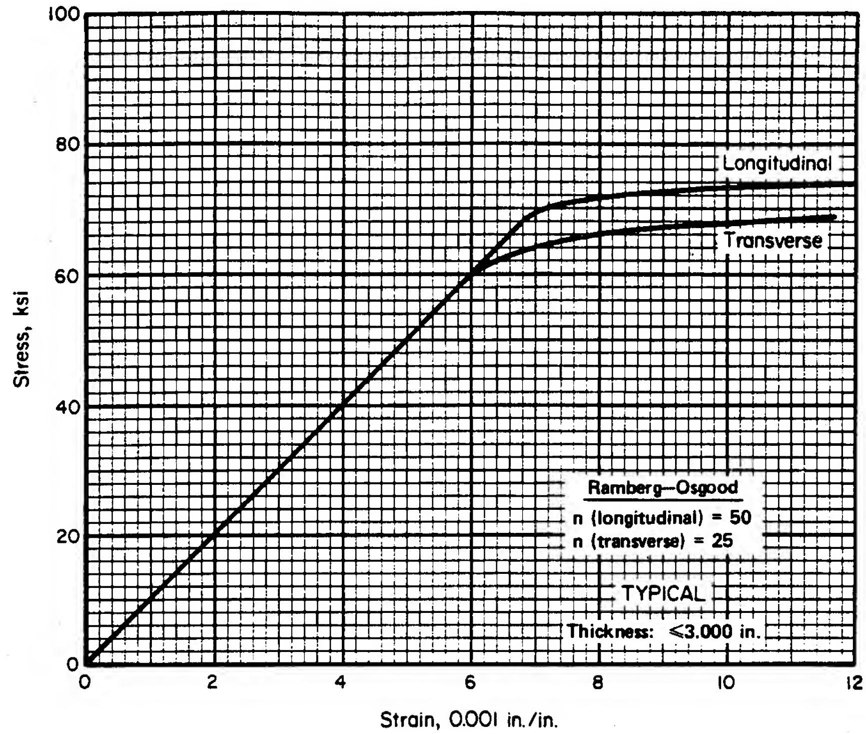

FIGURE 3.7.6.2.6(a). *Typical tensile stress-strain curves for 7175-T74 aluminum alloy die forging at room temperture.*

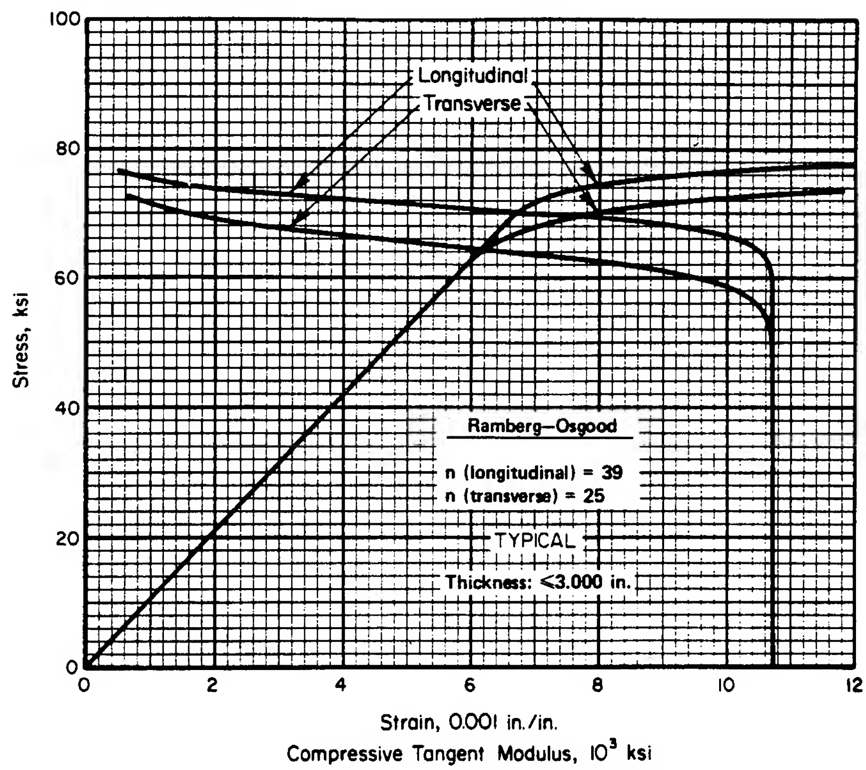

FIGURE 3.7.6.2.6(b). *Typical compressive stress-strain and compressive tangent-modulus curves for 7175-T74 aluminum alloy die forging at room temperature.*

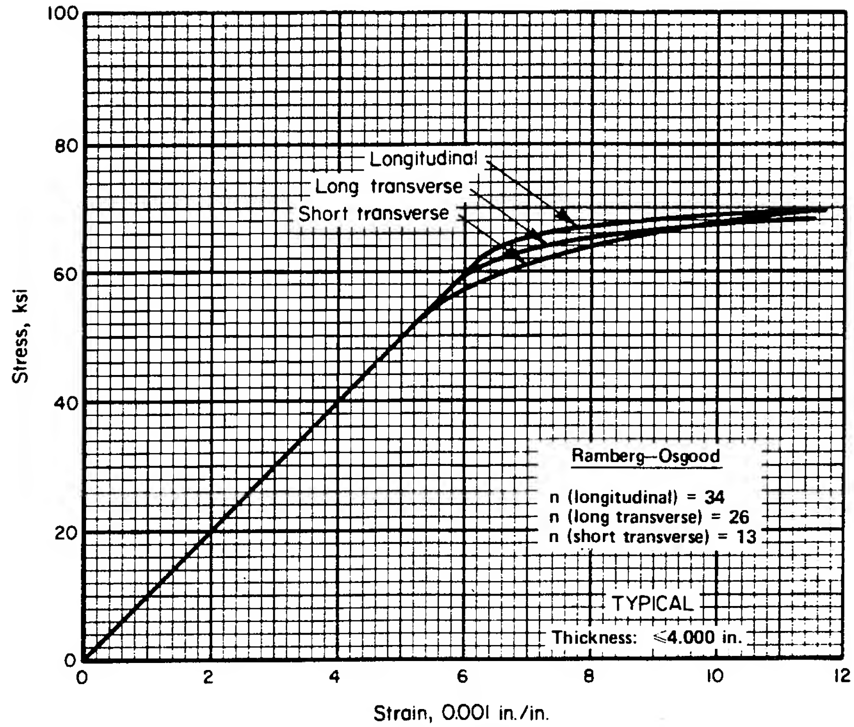

FIGURE 3.7.6.2.6(c). *Typical tensile stress-strain curves for 7175-T74 aluminum alloy hand forging at room temperature.*

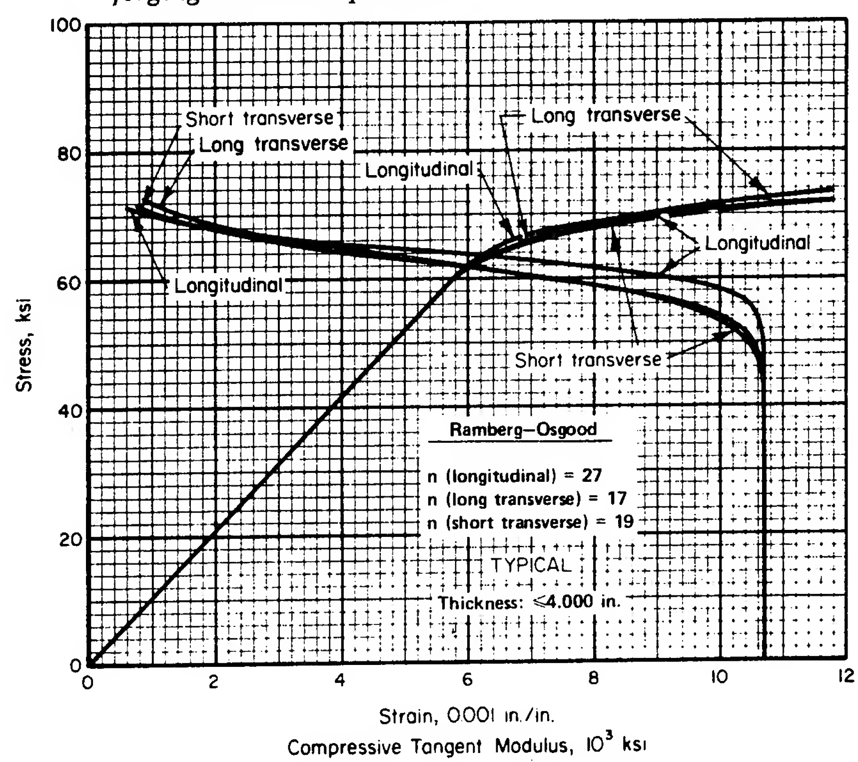

FIGURE 3.7.6.2.6(d). *Typical compressive stress-strain and compressive tangent-modulus curves for 7175-T74 aluminum alloy hand forging at room temperature.*

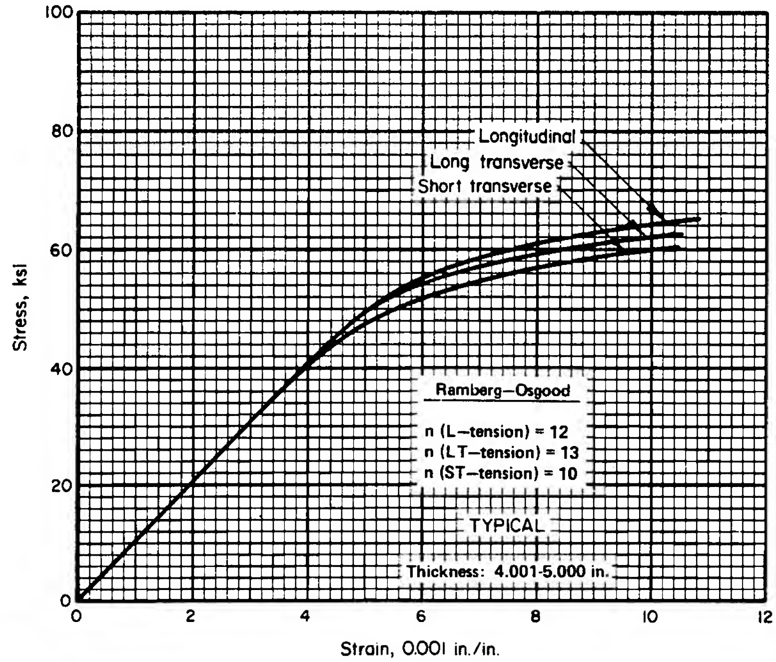

FIGURE 3.7.6.2.6(e). *Typical tensile stress-strain curves for aluminum alloy 7175-T7452 hand forging at room temperture.*

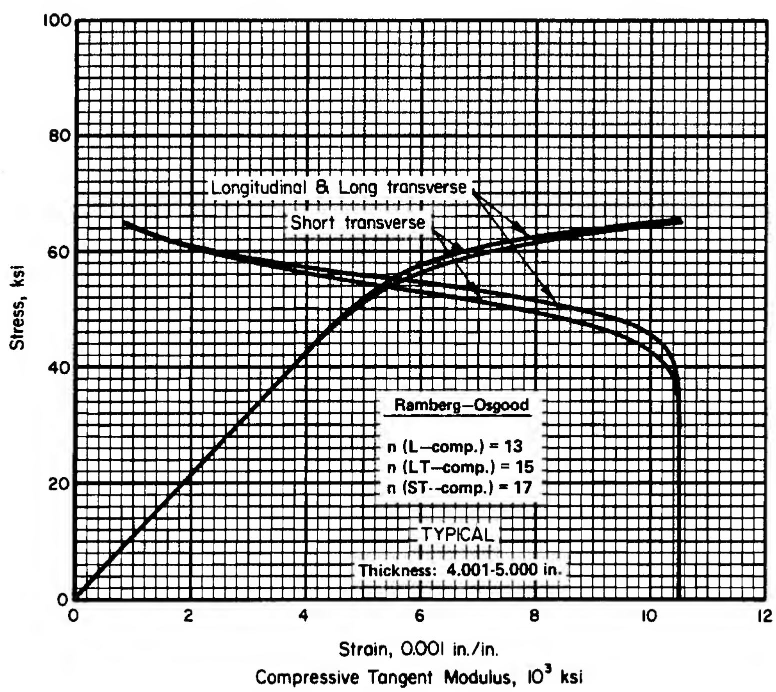

FIGURE 3.7.6.2.6(f). *Typical compressive stress-strain and compressive tangent-modulus curves for aluminum alloy 7175-T7452 hand forging at room temperature.*

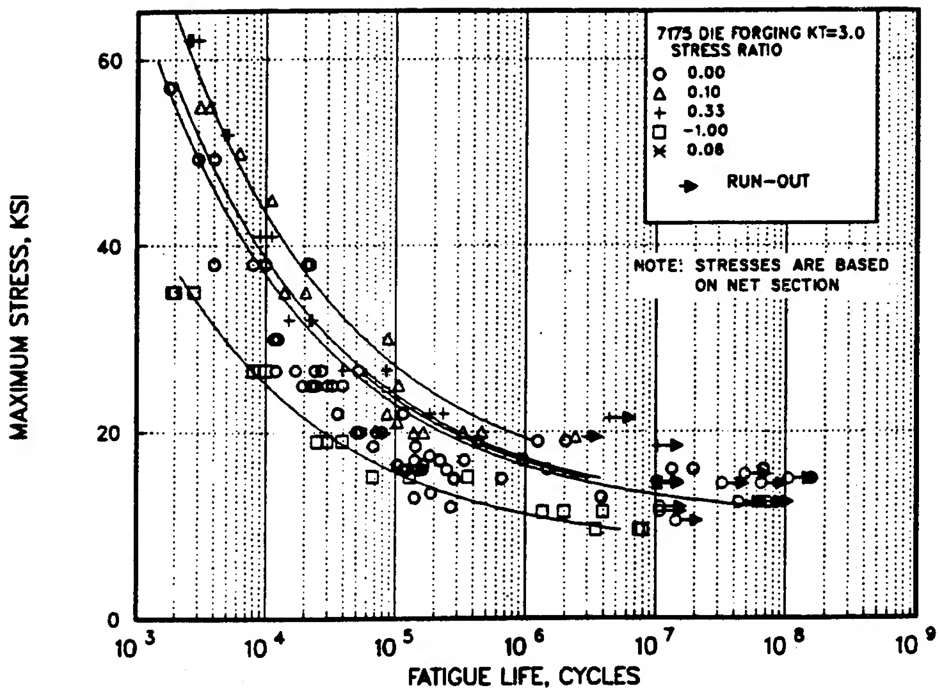

FIGURE 3.7.6.2.8(a). *Best-fit S/N curves for notched, K_t=3.0, 7175-T74 alloy die forging, longitudinal direction.*

Correlative Information for Figure 3.7.6.2.8(a)

Product Form: Die forging, 2.0 to 3.0-inch thick, unspecified thickness

Properties: TUS, ksi 77-82; TYS, ksi 69-75

TUS, ksi	TYS, ksi
77-82	69-75

Specimen Details: Circumferential notch, K_t=3
0.3-inch gross diameter
0.25-inch net diameter
Rectangular notched 0.10 x 0.20-inch

Surface Condition: Not specified

References: 3.2.5.1.9(d), 3.72.1.8(c), (d), 3.7.6.2.8(a), (b), and (c)

Test Parameters:
Loading - Axial
Frequency - 1200 cpm unspecified
Temperature - 70 F
Environment - Air

No. of Heats/Lots: 13

Equivalent Stress Equation:
Log N_f = 7.88-3.09 (S_{eq} - 7.15)
$S_{eq} = S_a + 0.37\ S_m$
Standard Deviation in Log (Life) = 7.38 (1/S_{eq})
Adjusted R^2 = 83

Sample Size: 137

[Caution: The equivalent stress model may provide unrealistic life predictions for stress ratios beyond those represented above]

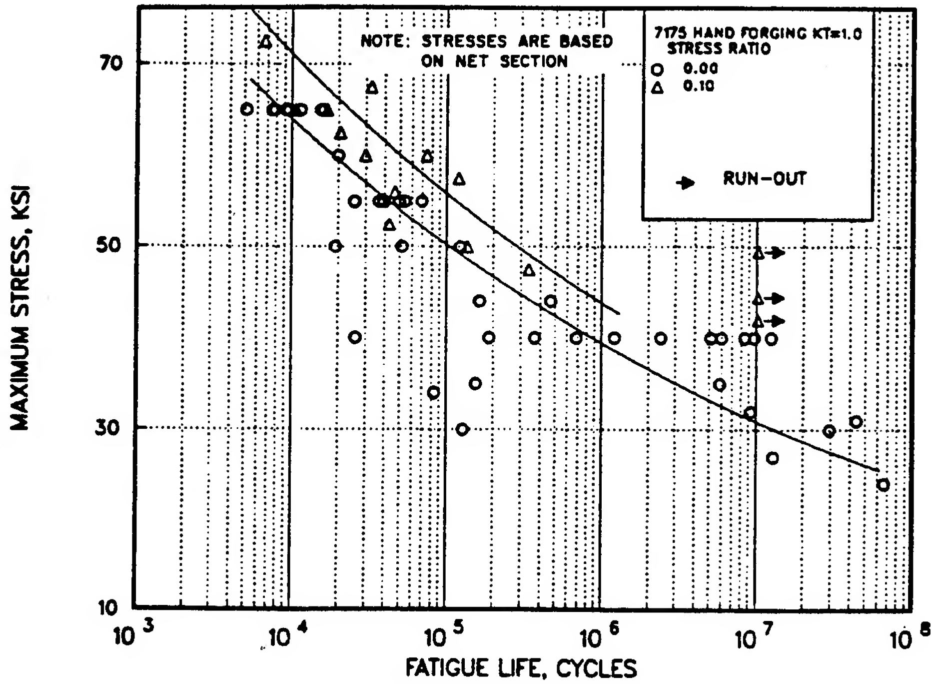

FIGURE 3.7.6.2.8(b). *Best-fit S/N curves for unnotched 7175-T74 alloy hand forging, longitudinal and transverse directions.*

Correlative Information for Figure 3.7.6.2.8(b)

Product Form: Hand forging, 2.0 to 6.25-inch thick

Properties:

TUS, ksi	TYS, ksi	Temp., F
71-77	60-68	70

Specimen Details: Uniform gage length
3.0-inch diameter
Hourglass gage section
0.25-inch minimum diameter

Surface Condition: Not specified

References: 3.2.5.1.9(d), 3.7.2.1.8(c) and (d)

Test Parameters:
Loading - Axial
Frequency - 1200 cpm
Temperature - 20 F
Environment - Air

Equivalent Stress Equation:
$\text{Log } N_f = 21.15\text{-}9.49 \log (S_{eq})$
$S_{eq} = S_{max} (1\text{-}R)$
Standard Deviation in Log (Life) = 23.33 ($1/S_{eq}$)
Adjusted R^2 = 76

[Caution: The equivalent stress model may provide unrealistic life predictions for stress ratios beyond those represented above]

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3.7.7 7475 ALLOY

3.7.7.0 *Comments and Properties.*—7475 is a Al-Zn-Mg-Cu alloy developed for applications requiring the high strength of 7075 but having fracture toughness superior to that of 7075. Sheet is available in the T61 and T761 tempers and plate in the T651 and T7651 tempers. Sheet has strength approximately the same as that of 7075 combined with toughness about the same as 2024-T3 at room temperature. Plate has strengths similar to those of corresponding tempers of 7075; the toughness of 7475-T651 equals or exceeds that of 7075-T7351.

Resistance to stress-corrosion cracking and exfoliation are comparable to that of 7075. The T73-type temper provides for much improved stress-corrosion resistance over T6-type temper with a decrease in strength. The T76-type temper provides for improved exfoliation resistance and stress-corrosion resistance over T6-type temper with some decrease in strength. Refer to Section 3.1.2.3.1 for information regarding resistance to stress-corrosion cracking.

Refer to Section 3.1.3.4 for comments regarding the weldability of the alloy.

Material specifications are shown in Table 3.7.7.0(a). Room-temperature mechanical and physical properties are shown in Tables 3.7.7.0(b) through (d).

TABLE 3.7.7.0(a). *Material Specifications for 7475 Aluminum Alloy*

Specification	Form
AMS 4084 (T61)	Bare sheet
AMS 4085 (T761)	Bare sheet
AMS 4090 (T651)	Bare plate
AMS 4089 (T7651)	Bare plate
AMS 4202 (T7351)	Bare plate
AMS 4207 (T61)	Clad sheet
AMS 4100 (T761)	Clad sheet

The temper index for 7475 is as follows:

Section	Temper
3.7.7.1	T61 and T651
3.7.7.2	T7351
3.7.7.3	1761 and T7651

3.7.7.1 *T61 and T651 Tempers.*—Figures 3.7.7.1.6(a) through (f) present tensile and compressive stress-strain and tangent-modulus curves for T61 sheet and T651 plate. Figure 3.7.7.1.6(g) contains full-range tensile curves for T61 sheet. Fatigue data for sheet are shown in Figures 3.7.7.1.8(a) through (c). Graphical displays of the residual behavior strength of center-cracked panels are presented in Figures 3.7.7.1.10(a) through (d).

3.7.7.2 *T7351 Temper.*—Figures 3.7.7.2.6(a) and (b) present tensile and compressive stress-strain and tangent-modulus curves for T7351 plate. Fatigue data for 7475-T7351 plate are presented in Figures 3.7.7.2.8(a) and (b). Figures 3.7.7.2.9(a) and (b) present fatigue-crack-propagation data for T7351 plate.

3.7.7.3 *T761 and T7651 Tempers.*—Figures 3.7.7.3.6(a) through (j) present tensile and compressive stress-strain and tangent-modulus curves for T761 bare and clad sheet and T7651 plate. Figures 3.7.7.3.6(k) and (1) contain full-range tensile stress-strain curves for T761 bare and clad sheet, respectively. Fatigue data for 7475-T761 sheet are presented in Figures 3.7.7.1.8(a) through (c). Fatigue data for 7475-T7651 plate are shown in Figure 3.7.7.2.8(b). Graphical displays of the residual strength behavior of center-cracked tension panels are presented in Figures 3.7.7.3.10(a) and (b).

TABLE 3.7.7.0(b). *Design Mechanical and Physical Properties of 7475 Aluminum Alloy Sheet and Plate*

Specification	AMS 4084	AMS 4090			AMS 4085			AMS 4089		
Form	Sheet	Plate			Sheet			Plate		
Temper	T61	T651			T761			T7651		
Thickness, in.	0.040-0.249	0.250-0.499	0.500-1.000	1.001-1.500	0.040-0.062	0.063-0.187	0.188-0.249	0.250-0.499	0.500-1.000	1.001-1.500
Basis	S	S	S	S	S	S	S	S	S	S
Mechanical Properties:										
F_{tu}, ksi:										
L	75	77	77	77	71	71	71	70	69	69
LT	75	78	78	78	71	71	71	71	70	70
F_{ty}, ksi:										
L	66	69	70	70	61	61	61	60	59	59
LT	64	67	68	68	60	60	60	60	59	59
F_{cy}, ksi:										
L	64	67	68	67	60	59	58	60	59	59
LT	68	70	71	71	61	63	63	63	62	59
F_{su}, ksi	45	44	43	41	43	42	41	41	39	37
F_{bru}[a], ksi:										
(e/D = 1.5)	120	113	113	113	112	112	111	104	103	103
(e/D = 2.0)	154	144	144	144	143	143	142	136	134	134
F_{bry}[a], ksi:										
(e/D = 1.5)	97	91	93	93	90	90	90	82	81	81
(e/D = 2.0)	110	106	107	107	104	104	104	97	95	95
e, percent:										
L	9	10	9	9	9	9	9	9	8	6
LT	9	10	9	9	9	9	9	9	8	6
E, 10^3 ksi	10.0	10.2			10.0			10.2		
E_c, 10^3 ksi	10.5	10.6			10.5			10.6		
G, 10^3 ksi	3.8	3.9			3.8			3.9		
μ	0.33	0.33			0.33			0.33		
Physical Properties:										
ω, lb/in.^{3}	0.101									
C, K, and α	0.23 (at 212 F)									
K, Btu/[(hr)(ft^2)(F)/ft]	80 (at 77 F) for T61 and T651; 90 (at 77 F) for T761 and T7651									
α, 10^{-6} in./in./F	12.9 (68 to 212 F)									

[a] See Table 3.1.2.1.1 Bearing values are "dry pin" values per Section 1.4.7.1.

TABLE 3.7.7.0(c). *Design Mechanical and Physical Properties of 7475 Aluminum Alloy Plate*

Specification	AMS 4202											
Form	Plate											
Temper	T7351											
Thickness, in.	0.250-1.500		1.501-2.000		2.001-2.500		2.501-3.000		3.001-3.500		3.501-4.000	
Basis	A	B	A	B	A	B	A	B	A	B	A	B
Mechanical Properties:												
F_{tu}, ksi:												
L	70	72	70	71	68	70	68	69	64	67	64	66
LT	71	73	70	72	68	70	68	69	64	68	64	67
ST	66[b]	70[b]	65	69	65	69	65	68	63	67	63	66
F_{ty}, ksi:												
L	59	62	58	60	56	59	56	58	52	56	52	54
LT	60	62	58[c]	61	56	59	56	58	52	56	52	54
ST	54[b]	57[b]	53	56	53	56	53	55	50	53	50	52
F_{cy}, ksi:												
L	58	60	56	59	54	57	53	55	49	53	49	51
LT	61	63	60	63	58	61	58	60	54	58	54	56
ST	62	64[b]	60	63	58	61	58	60	54	58	54	56
F_{su}, ksi	41	42	42	43	41	42	41	42	39	42	39	41
F_{bru}[a], ksi:												
(e/D = 1.5)	102	105	103	106	101	104	101	103	97	102	97	101
(e/D = 2.0)	132	136	134	138	131	135	131	134	125	133	125	131
F_{bry}[a], ksi:												
(e/D = 1.5)	81	84	82	86	81	84	81	84	77	82	77	80
(e/D = 2.0)	97	101	97	102	95	100	95	99	89	96	89	93
e, percent (S-basis):												
L	10	...	10	...	10	...	10	...	10	...	9	...
LT	9	...	8	...	8	...	8	...	8	...	7	...
ST	4[b]	...	4	...	4	...	3	...	3	...	3	...
E, 10^3 ksi	10.3											
E_c, 10^3 ksi	10.6											
G, 10^3 ksi	3.9											
μ	0.33											
Physical Properties:												
ω, lb/in.^{3}	0.101											
C, Btu/(lb)(F)	0.21 (at 212 F)											
K, Btu/[(hr)(ft^2)(F)/ft]	94 (at 77 F)											
α, 10^{-6} in./in./F	13.0 (68 to 212 F)											

[a]See Table 3.1.2.1.1 Bearing values are "dry pin" values per Section 1.4.7.1.
[b]Values applicable to 1.500-inch thickness only.
[c]S-basis. The A-value for F_{ty}(LT) = 59 ksi.

TABLE 3.7.7.0(d). *Design Mechanical and Physical Properties of Clad 7475 Aluminum Alloy Sheet*

Specification	AMS 4207			AMS 4100					
Form	Sheet								
Temper	T61			T761					
Thickness, in.	0.040-0.062	0.063-0.187		0.188-0.249	0.040-0.062	0.063-0.187		0.188-0.249	
Basis	S	A	B	S	S	A	B	A	B
Mechanical Properties:									
F_{tu}, ksi:									
L	69	69	73	72	66	67	70	68	71
LT	69	70	73	72	66	68	70	70	72
F_{ty}, ksi:									
L	61	64	67	63	56	58	61	59	63
LT	59	60[b]	64	61	55	57	60	60	62
F_{cy}, ksi:									
L	60	61	65	62	55	56	59	58	60
LT	63	64	68	65	58	59	62	61	63
F_{su}, ksi	42	40	41	39	41	40	41	40	41
F_{bru}[a], ksi:									
(e/D = 1.5)	110	111	116	115	104	106	110	108	111
(e/D = 2.0)	140	142	148	146	133	136	140	138	142
F_{bry}[a], ksi:									
(e/D = 1.5)	89	90	96	92	83	86	90	90	93
(e/D = 2.0)	102	104	111	106	97	101	106	106	110
e, percent (S-basis):									
LT	9	9	...	9	9	9	...	9	...
E, 10^3 ksi:									
Primary	10.0	10.0		10.0	10.0	10.0		10.0	
Secondary	9.2	9.4		9.7	9.2	9.4		9.7	
E_c, 10^3 ksi:									
Primary	10.5	10.5		10.5	10.5	10.5		10.5	
Secondary	9.4	9.7		10.0	9.4	9.7		10.0	
G, 10^3 ksi	3.8	3.8		3.8	3.8	3.8		3.8	
μ	0.33	0.33		0.33	0.33	0.33		0.33	
Physical Properties:									
ω, lb/in.^{3}	0.101								
C, K, α	...								

[a]Bearing values are "dry pin" values per Section 1.4.7.1.
[b]S-basis. The A-value is 61 ksi.

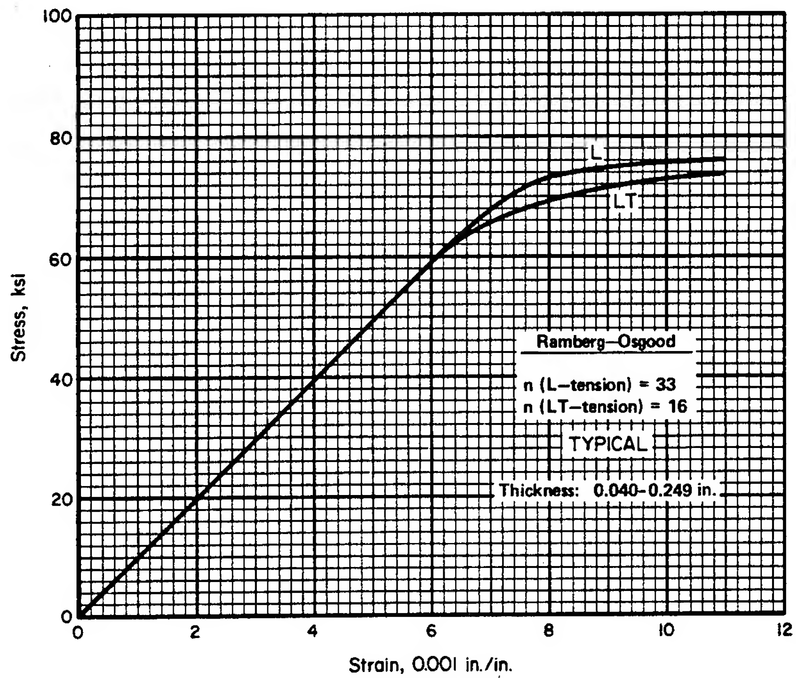

FIGURE 3.7.7.1.6(a). *Typical tensile stress-strain curves for 7475-T61 aluminum alloy sheet at room temperature.*

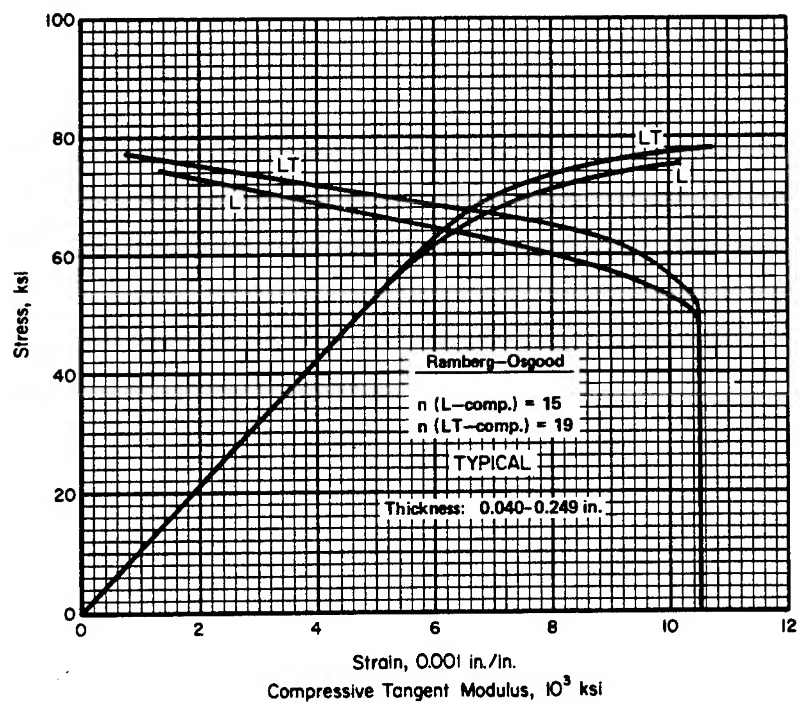

FIGURE 3.7.7.1.6(b). *Typical compressive stress-strain and compressive tangent-modulus curves for 7475-T61 aluminum alloy sheet at room temperature.*

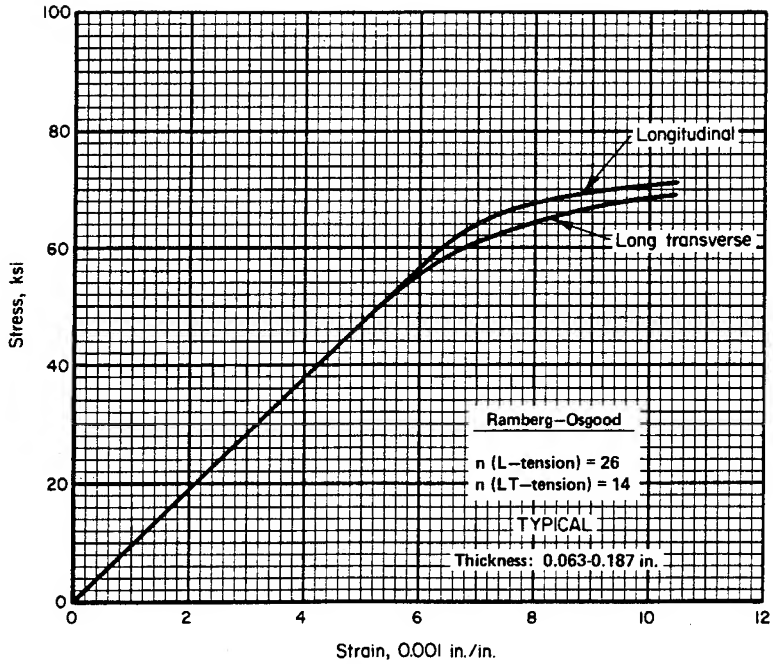

FIGURE 3.7.7.1.6(c). *Typical tensile stress-strain curves for clad 7475-T61 aluminum alloy sheet at room temperature.*

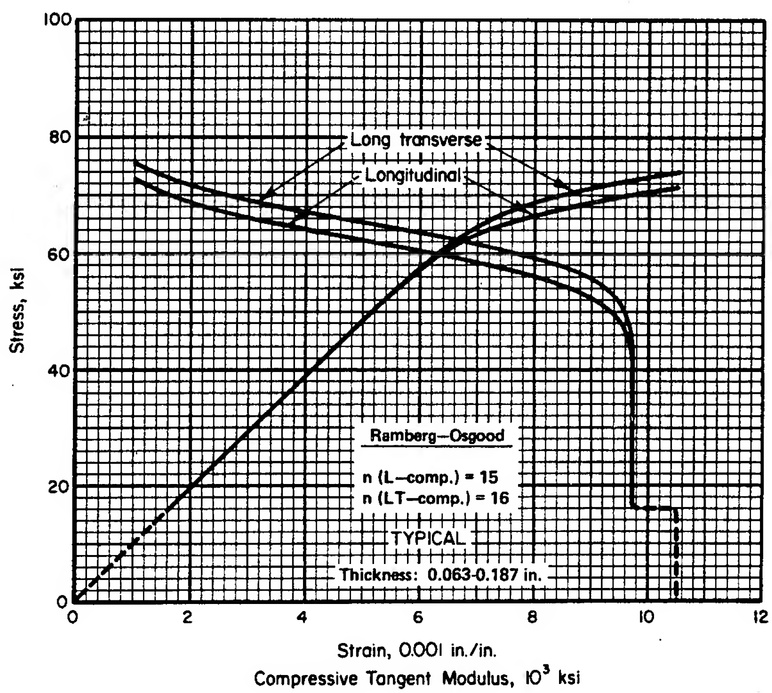

FIGURE 3.7.7.1.6(d). *Typical compressive stress-strain and compressive tangent-modulus curves for clad 7475-T61 aluminum alloy sheet at room temperature.*

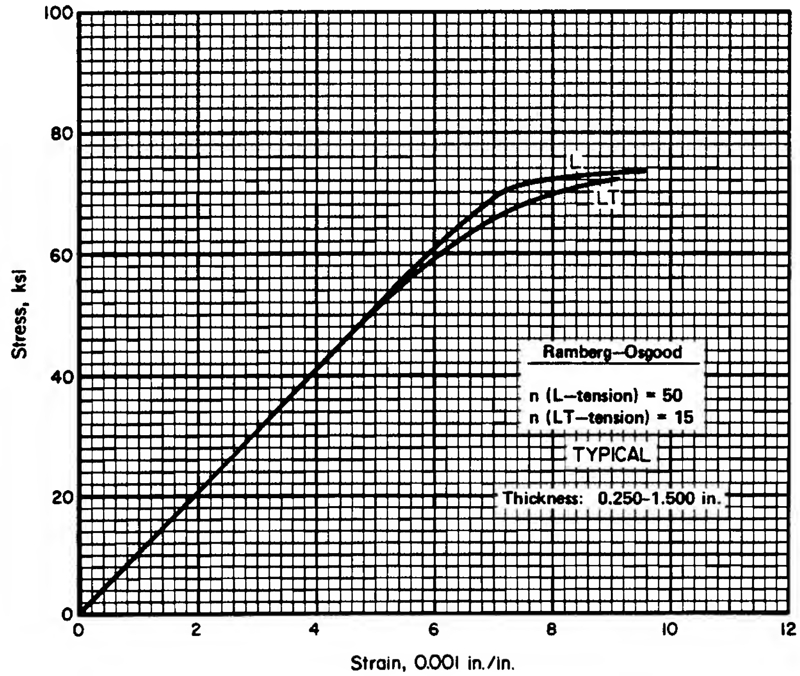

FIGURE 3.7.7.1.6(e). *Typical tensile stress-strain curves for 7475-T651 aluminum alloy plate at room temperature.*

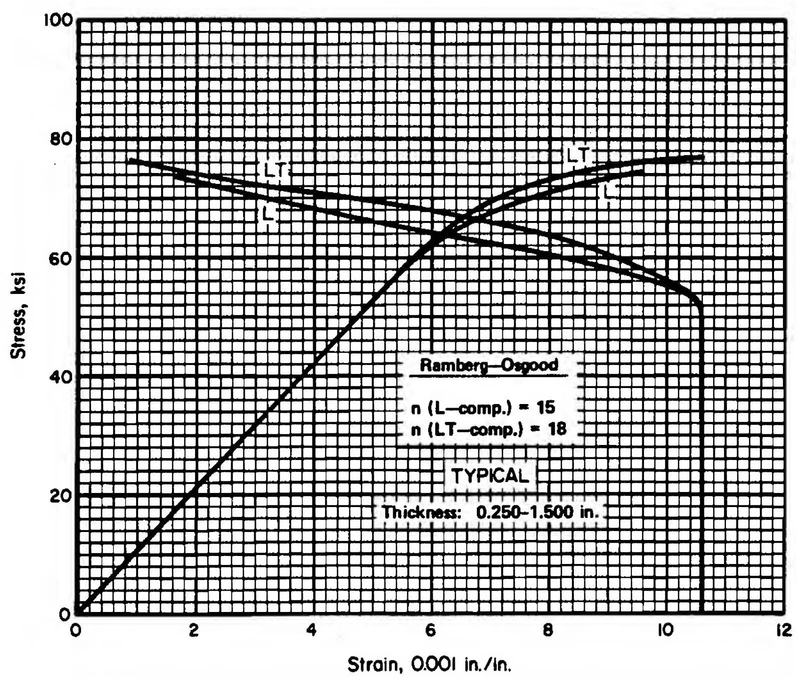

FIGURE 3.7.7.1.6(f). *Typical compressive stress-strain and compressive tangent-modulus curves for 7475-T651 aluminum alloy plate at room temperature.*

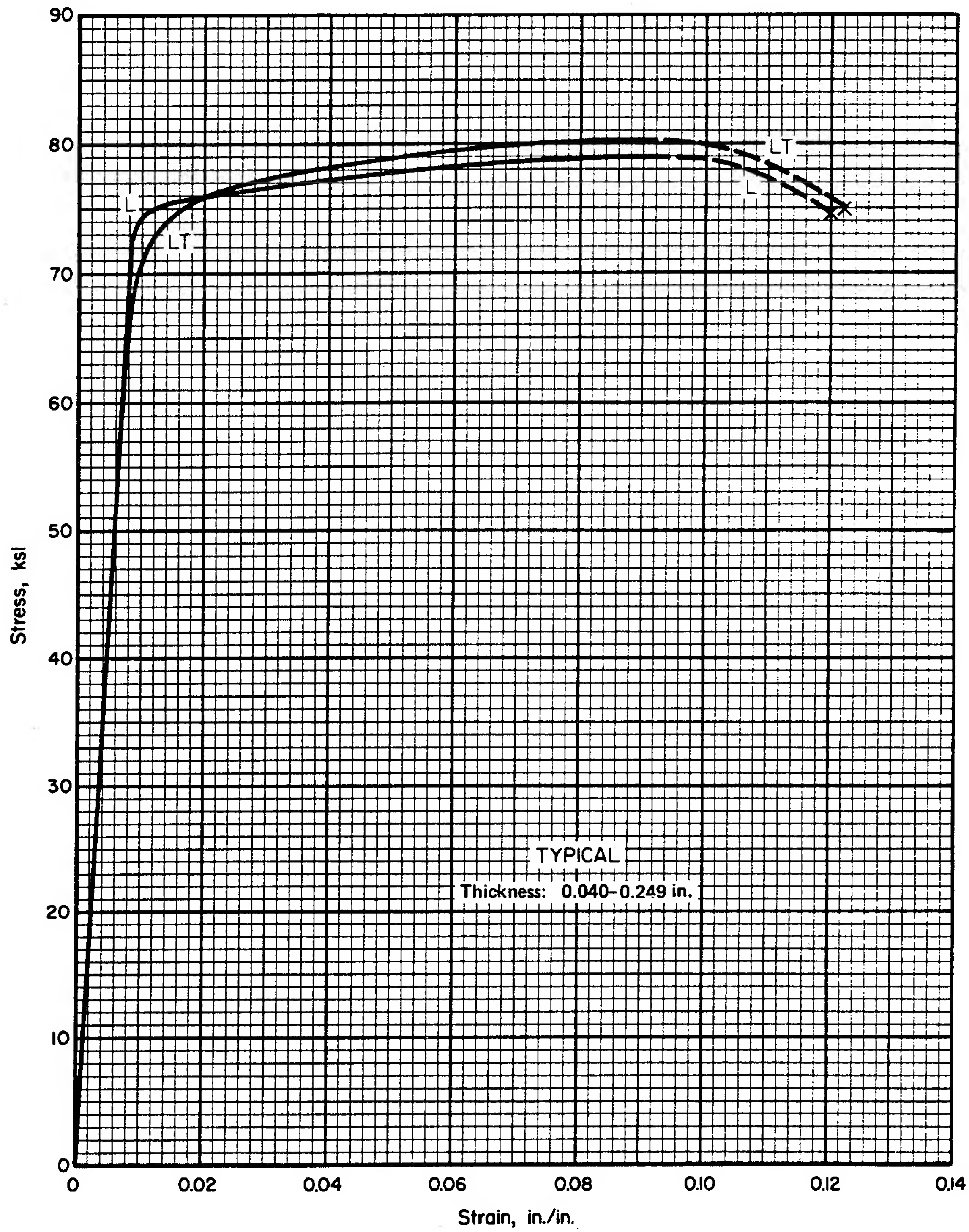

FIGURE 3.7.7.1.6(g). *Typical tensile stress-strain curves (full range) for 7475-T61 aluminum alloy sheet at room temperature.*

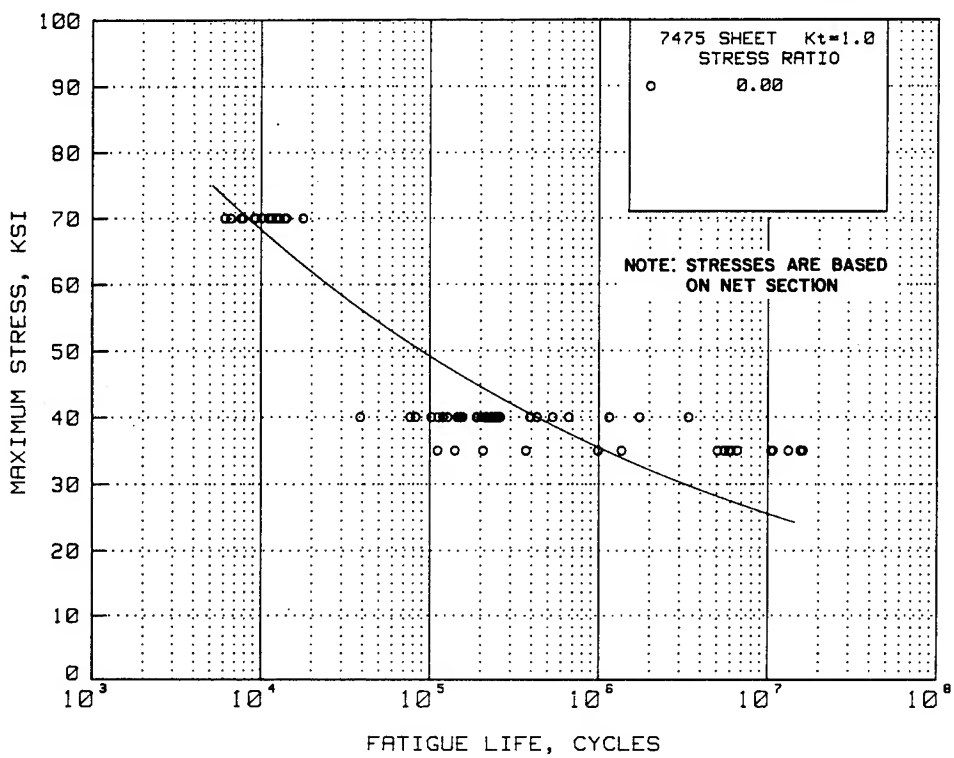

FIGURE 3.7.7.1.8(a). *Best-fit S/N curve for unnotched 7475-T61 and T761 sheet, thickness ≤0.125 inch, longitudinal and long transverse directions.*

Correlative Information for Figure 3.7.7.1.8(a)

Product Form: Sheet, 0.032-inch through 0.125-inch thick

Properties:	TUS, ksi	TYS, ksi	Temp.,F
T61	81	73-75	RT
T761	77	68-70	RT

Specimen Details: Unnotched, hourglass, 0.500-inch diameter
4.00-inch test section radius, r

Surface Condition: As machined

References: 3.2.5.1.9(d)

Test Parameters:
Loading - Axial
Frequency - 798, 1500, or 1728 cpm
Temperature - RT
Environment - Air

No. of Heats/Lots: 2

Equivalent Stress Equation:
$\text{Log } N_f = 16.9 - 7.03 \log (S_{max})$
Standard Error of Estimate=0.545
Standard Deviation in Life=0.988
$R^2 = 70\%$

Sample Size=67

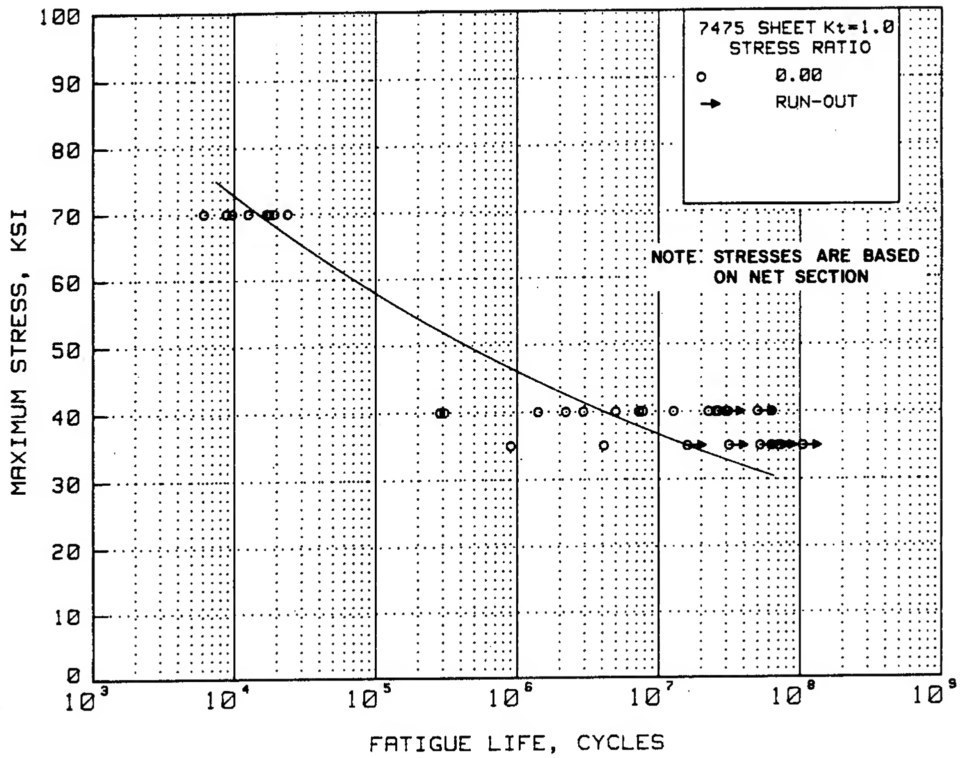

FIGURE 3.7.7.1.8(b). *Best-fit S/N curve for unnotched 7475-T61 and T761 sheet, thickness 0.125 inch, longitudinal and long transverse directions.*

Correlative Information for Figure 3.7.7.1.8(b)

Product Form: Sheet, 0.032-inch through 0.125-inch thick

Properties:	TUS, ksi	TYS, ksi	Temp.,F
T61	80-81	73-76	RT
T761	75	66-67	RT

Specimen Details: Unnotched, hourglass, 0.500-inch diameter 4.00-inch text section

Surface Condition: Not specified

Reference: 3.2.5.1.9(d)

Test Parameters:
Loading - Axial
Frequency - 798, 1500, 1728 cpm
Temperature - RT
Environment - Air

No. of Heats/Lots: 2

Equivalent Stress Equation:
Log N_f=16.9-7.03 log (S_{max})
Standard Error of Estimate=0.545
Standard Deviation in Life=0.988
R^2=70%

Sample Size=67

(Caution: The equivalent stress model may provide unrealistic life predictions for stress ratios beyond those represented above.)

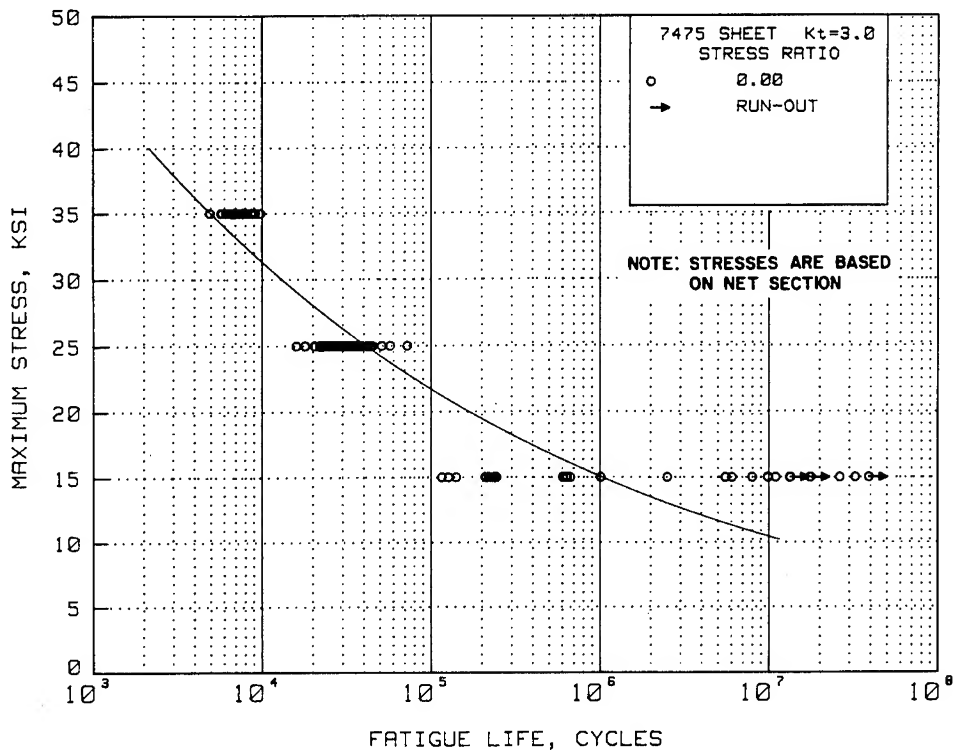

FIGURE 3.7.7.1.8(c). *Best-fit S/N curve for notched, K_t=3.0, 7475-T61 and T761 sheet, longitudinal and long transverse directions.*

Correlative Information for Figure 3.7.7.1.8(c)

Product Form: Sheet, 0.032-inch through 0.249-inch thick

Properties:	TUS, ksi	TYS, ksi	Temp.,F
T61	81-82	73-76	RT
T761	75-77	67-70	RT

Specimen Details: Notched, edge notched K_t=3.0
1.000-inch gross width
0.700-inch net width
0.050-inch root radius, r
60° flank angle, ω

Surface Condition: As machined

Reference: 3.2.5.1.9(d)

Test Parameters:
Loading - Axial
Frequency - 798, 1500, 1728 cpm
Temperature - RT
Environment - Air

No. of Heats/Lots: 2

Equivalent Stress Equation:
Log N_f=13.4-6.29 log (S_{max})
Standard Error of Estimate=0.441
Standard Deviation in Life=0.931
R^2=78%

Sample Size=99

(Caution: The equivalent stress model may provide unrealistic life predictions for stress ratios beyond those represented above.)

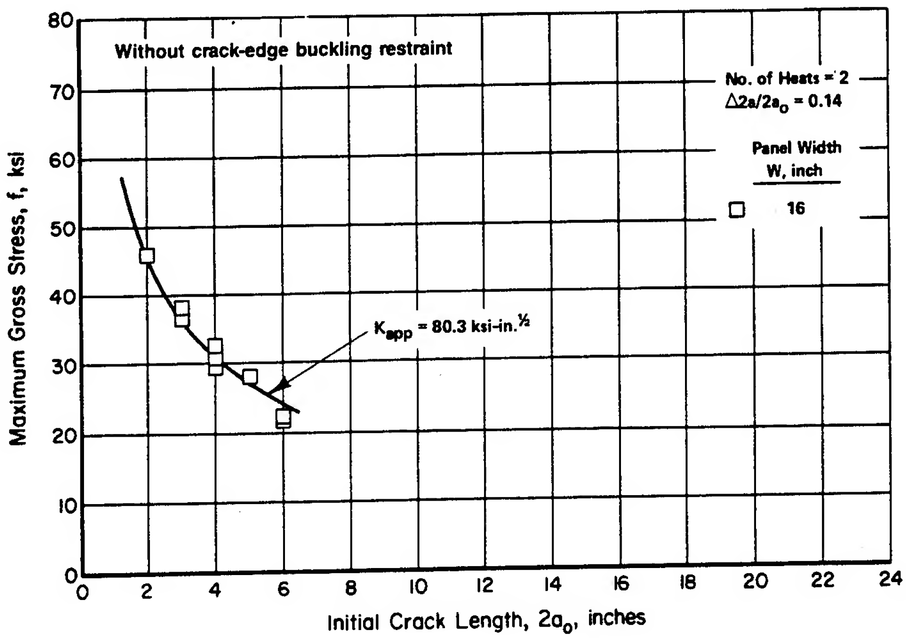

FIGURE 3.7.7.1.10(a). *Residual strength behavior of 0.063-inch-thick 7475-T61 aluminum alloy sheet at room temperature. Crack orientation is L-T. [References 3.1.2.1.6(d) and 3.2.5.1.9(d)].*

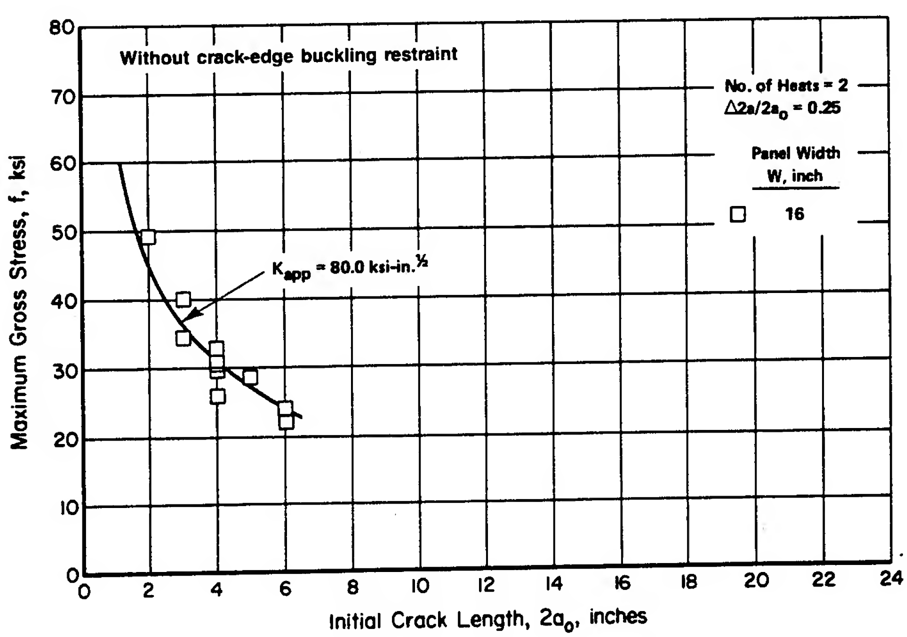

FIGURE 3.7.7.1.10(b). *Residual strength behavior of 0.063-inch-thick 7475-T61 aluminum alloy sheet at room temperature. Crack orientation is T-L. [References 3.1.2.1.6(d) and 3.2.5.1.9(d)].*

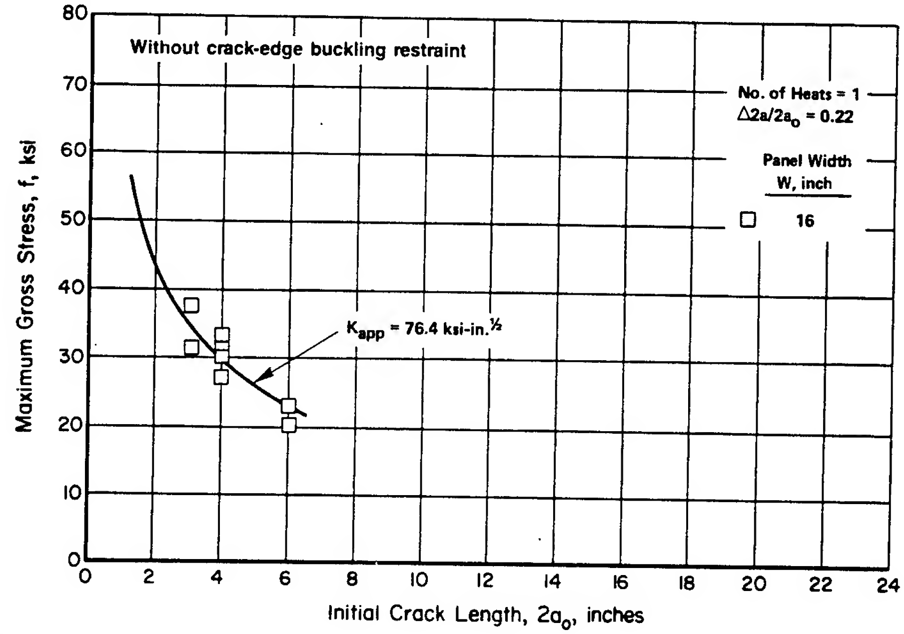

FIGURE 3.7.7.1.10(c). *Residual strength behavior of 0.063-inch-thick 7475-T61 clad aluminum alloy sheet at room temperature. Crack orientation is L-T. [Reference 3.2.5.1.9(d)].*

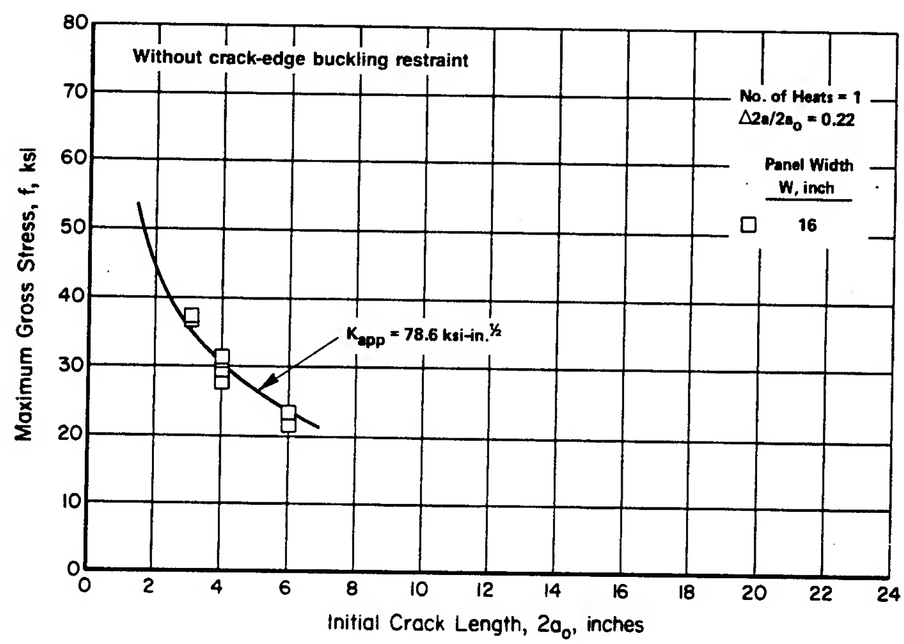

FIGURE 3.7.7.1.10(d). *Residual strength behavior of 0.063-inch-thick 7475-T61 clad aluminum alloy sheet at room temperature. Crack orientation is T-L. [Reference 3.2.5.1.9(d)].*

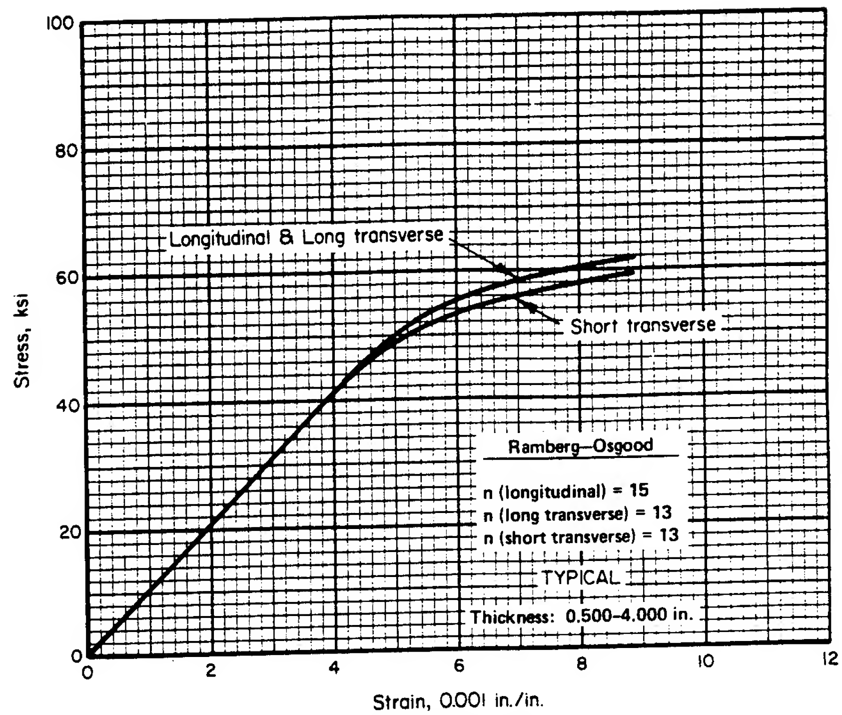

FIGURE 3.7.7.2.6(a). *Typical tensile stress-strain curves for 7475-T7351 aluminum alloy plate at room temperature.*

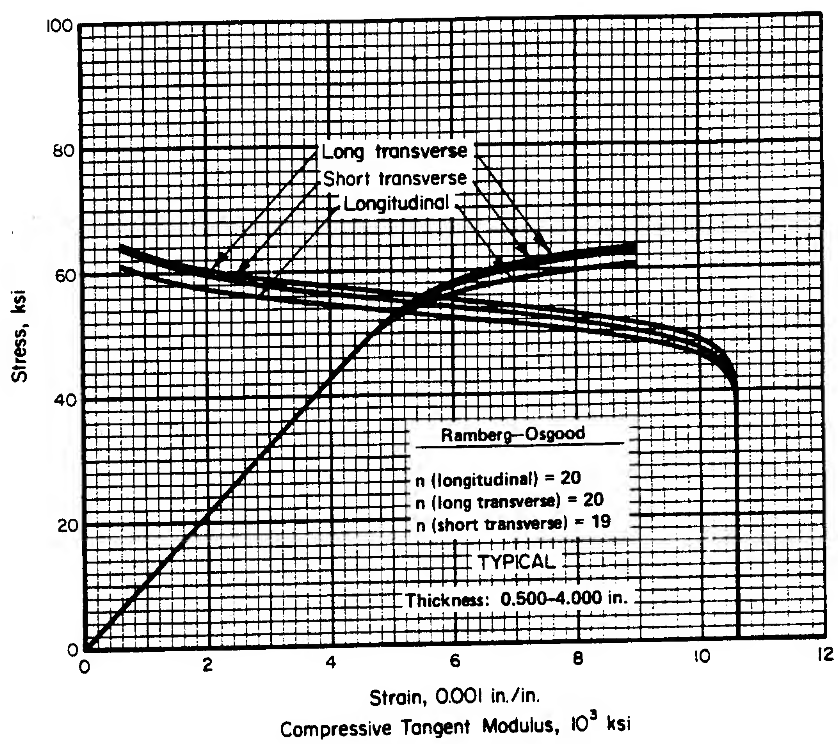

FIGURE 3.7.7.2.6(b). *Typical compressive stress-strain and compressive tangent-modulus curves for 7475-T7351 aluminum alloy plate at room temperature.*

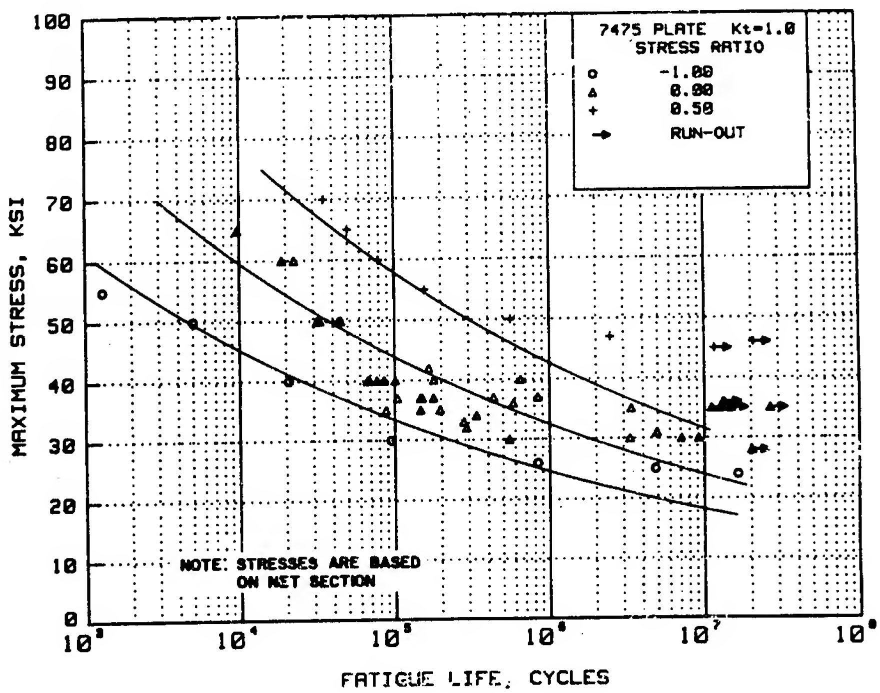

FIGURE 3.7.7.2.8(a). *Best-fit S/N curves for unnotched 7475-T7351plate, longitudinal and long transverse orientation.*

Correlative Information for Figure 3.7.7.2.8(a)

Product Form: Plate. 0.5. 1.0. 2.0. 3.0 and 4.0-inches thick

Properties:	TUS. ksi	TYS. ksi	Temp.. F
L	70	60	RT
LT	71	60	RT

Specimen Details: Unnotched
Hourglass, 0.300-inch net diameter
9.875-inch test section radius

Surface Condition: As machined

Reference: 3.7.7.2.8(a) and (b)

Test Parameters:
Loading - Axial
Frequency - Not specified
Temperature - RT
Environment - Air

No. of Heats/Lots: 5

Equivalent Stress Equation:
$\text{Log } N_f = 17.42 - 7.56 \text{ Log } (S_{eq})$
$S_{eq} = S_{max}(1-R)^{0.40}$
Standard Error of Estimate = 0.433
Standard Deviation in Life = 0.857
R^2 = 74%

Sample Size = 52

[Caution: The equivalent stress model may provide unrealistic life predictions for stress ratios beyond those represented above]

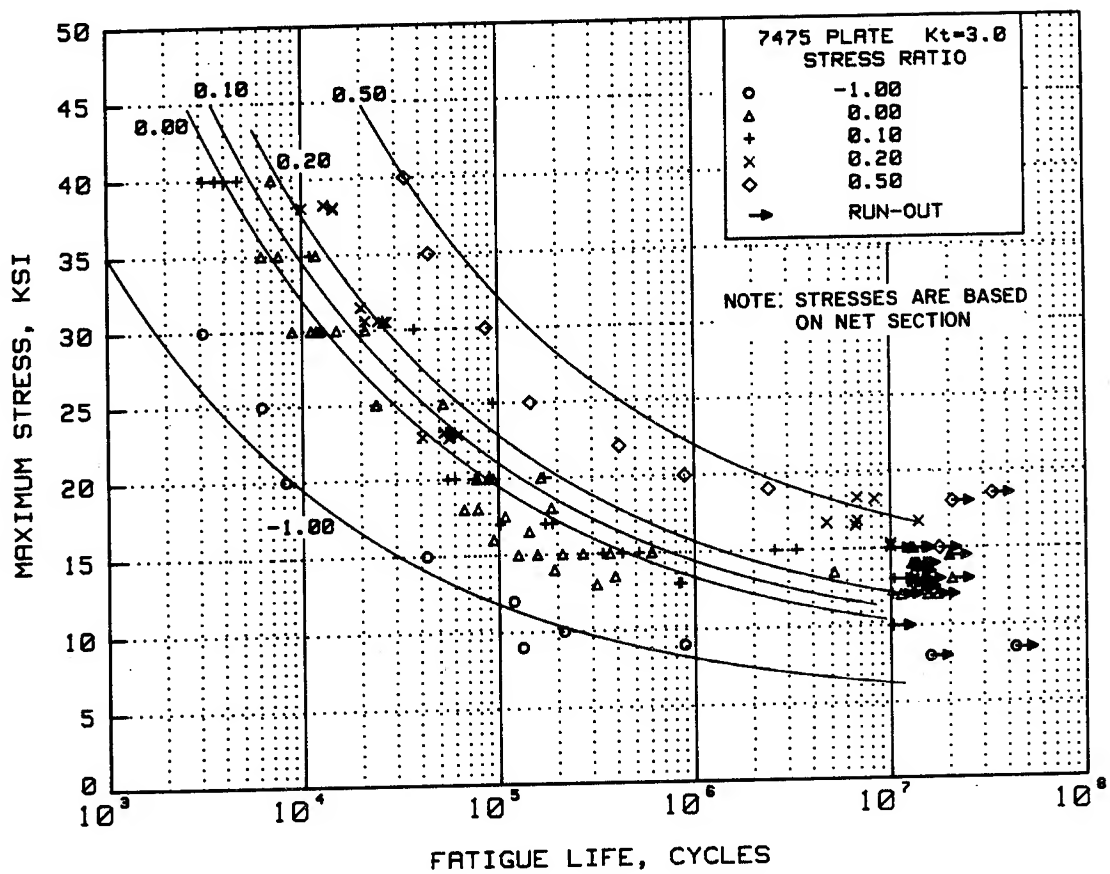

FIGURE 3.7.7.2.8(b). *Best-fit S/N curves for notched, K_t=3.0, 7475-T7351 and T7651 plate, longitudinal and long transverse direction.*

(See following page for correlative information).

Correlative Information for Figure 3.7.7.2.8(b)

Product Form: Plate, 0.5, 1.0, 1.5, 2.0, 3.0, and 4.0 inches thick

Properties:	TUS, ksi	TYS ksi	Temp., F
L (T7351)	70	60	RT (Ref. (a)
LT (T7351)	71	61	RT and (b))
L (T7351)	72	62	RT (Ref. (c))
(T7651)	Not specified		(Ref. (d))
L (T7351)	72	63	RT (Ref. (e))
LT (T7351)	73	62	RT (Ref. (e))

Specimen Details: Notched, $K_t = 3.0$

Circumferentially notched (Ref. (a) and (b))
- 0.253-inch gross width
- 0.147-inch net width
- 0.013-inch root radius, r
- 60° flank angle, ω

Edge notched (Ref. (c))
- 1.00-inch gross width
- 0.70-inch net width
- root radius not specified
- 60° flank angle, ω

Edge notched (Ref. (d))
- 2.25-inch gross width
- 1.50-inch net width
- 0.113-inch root radius, r
- 60° flank angle, ω

Circumferentially notched (Ref. (e))
- 1.375-inch gross width
- 0.25-inch net width
- 0.13-inch root radius, r
- 60° flank angle, ω

Reference: 3.7.7.2.8 (a) through (e)

Surface Condition:
Not specified (Ref. (a) and (b))
As machined and deburred (Ref. (c))
32 RMS (Ref. (d))
10 RMS (Ref. (e))

Test Parameters:
Loading - Axial
Frequency
- Not specified (Ref. (a) and (b))
- 1800 cpm (Ref. (c) and (d))
- 1500 cpm (Ref. (e))

Temperature - RT
Environment - Air

No. of Heats/Lots: 8

Equivalent Stress Equation:
$\log N_f = 8.46 - 3.21 \log (S_{eq} - 7.5)$
$S_{eq} = S_{max} (1-R)^{0.72}$
Standard Error of Estimate = 0.422
Standard Deviation in Life = 0.923
$R^2 = 79\%$

Sample Size = 97

[Caution: The equivalent stress model may provide unrealistic life predictions for stress ratios beyond those represented above]

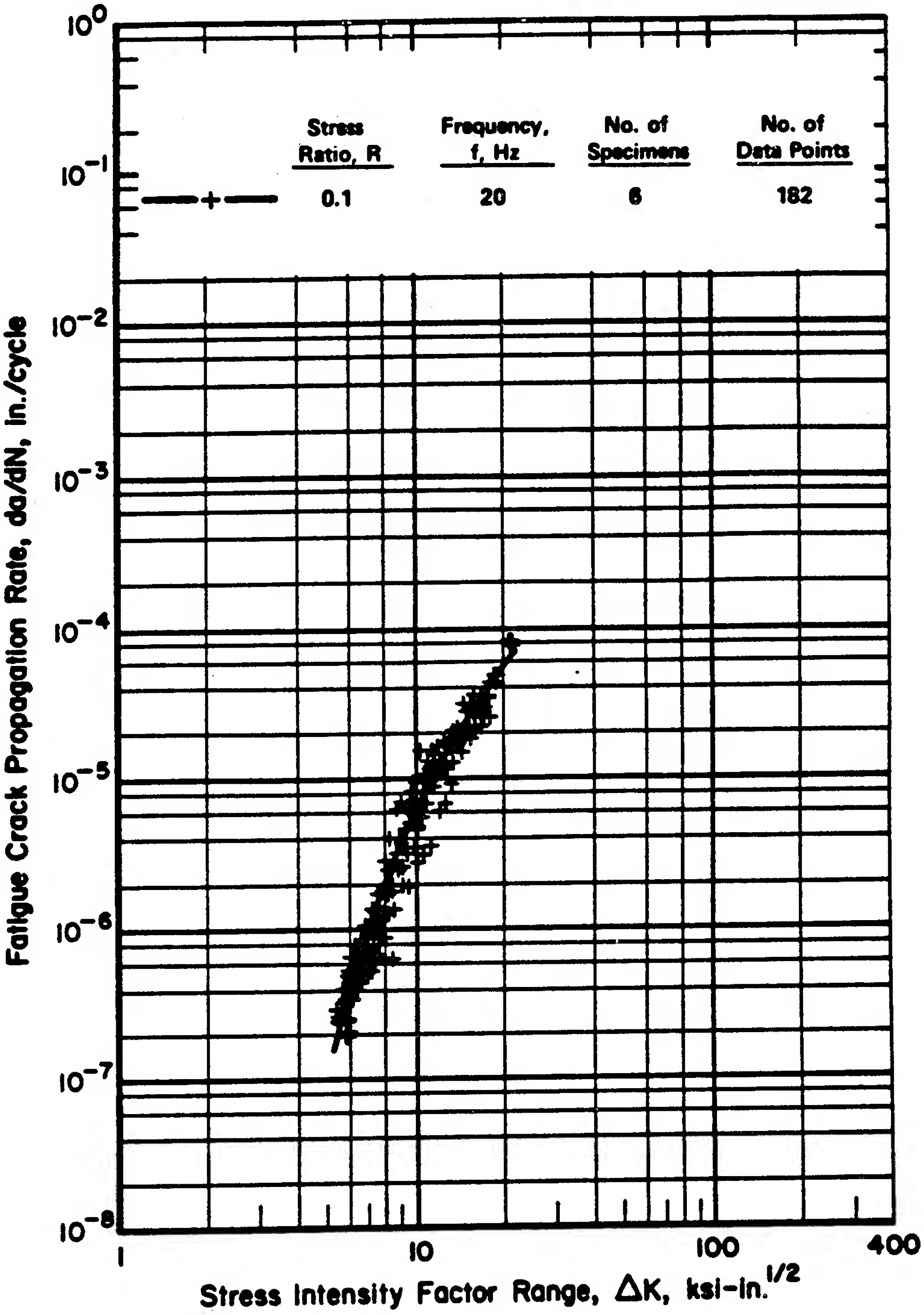

FIGURE 3.7.7.2.9(a). *Fatigue-crack-propagation data for 1.5-inch thick, 7475-T7351 aluminum alloy plate [References 3.7.7.2.9(a) and (b)].*

Specimen Thickness:	*0.650 inches*	*Environment:*	*Lab air*
Specimen Width:	*1.500 inches*	*Temperature:*	*RT*
Specimen Type:	*CT*	*Orientation:*	*L-T*

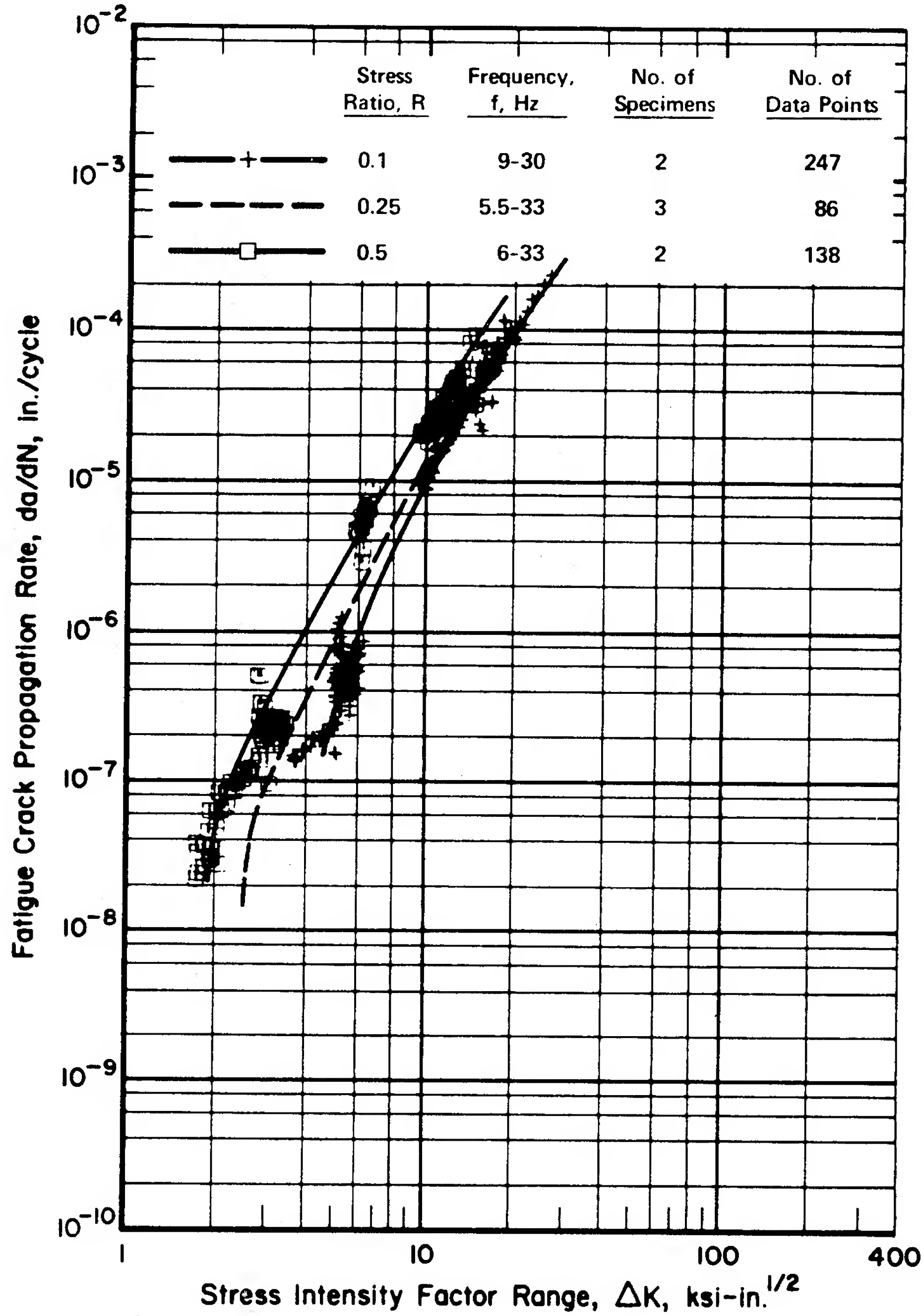

FIGURE 3.7.7.2.9(b). *Fatigue-crack-propagation data for 0.500-inch-thick, 7475-T7351 aluminum alloy plate [Reference 3.7.4.2.9(c)].*

Specimen Thickness:	*0.528 — 0.530 inches*	*Environment:*	*95% R.H.*
Specimen Width:	*4.6 inches*	*Temperature:*	*RT*
Specimen Type:	*CC*	*Orientation:*	*L-T*

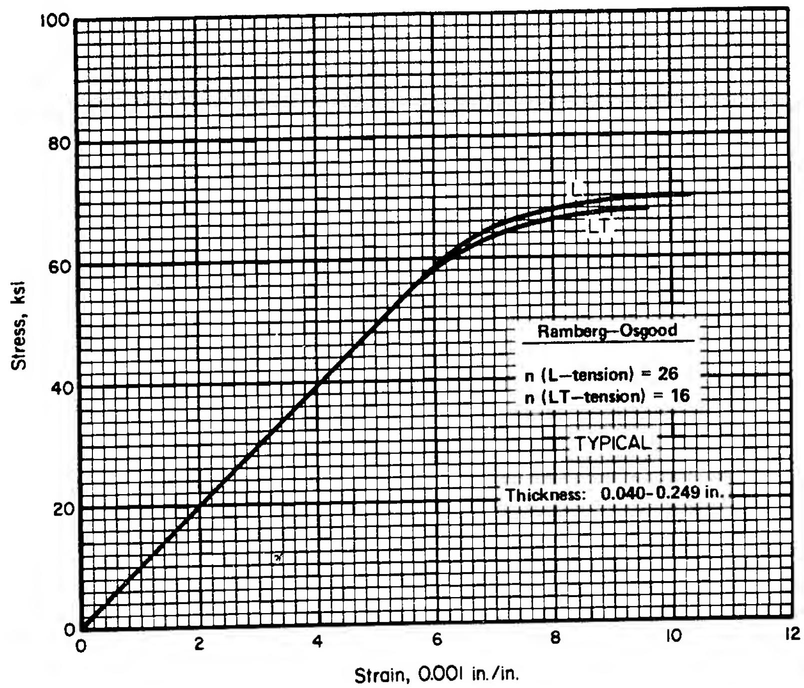

FIGURE 3.7.7.3.6(a). *Typical tensile stress-strain curves for 7475-T761 aluminum alloy sheet at room temperature.*

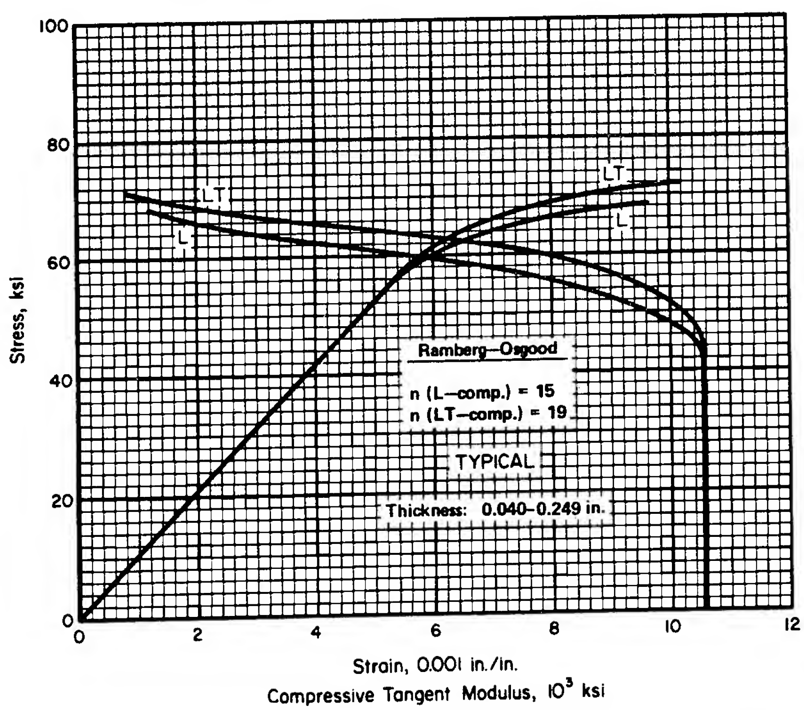

FIGURE 3.7.7.3.6(b). *Typical compressive stress-strain and compressive tangent-modulus curves for 7475-T761 aluminum alloy sheet at room temperature.*

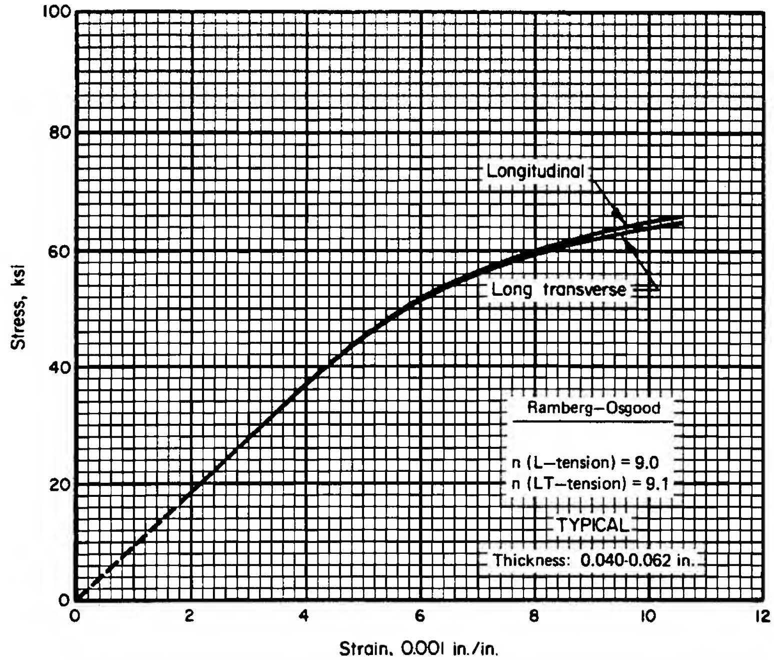

FIGURE 3.7.7.3.6(c). *Typical tensile stress-strain curves for clad 7475-T761 aluminum alloy sheet at room temperature.*

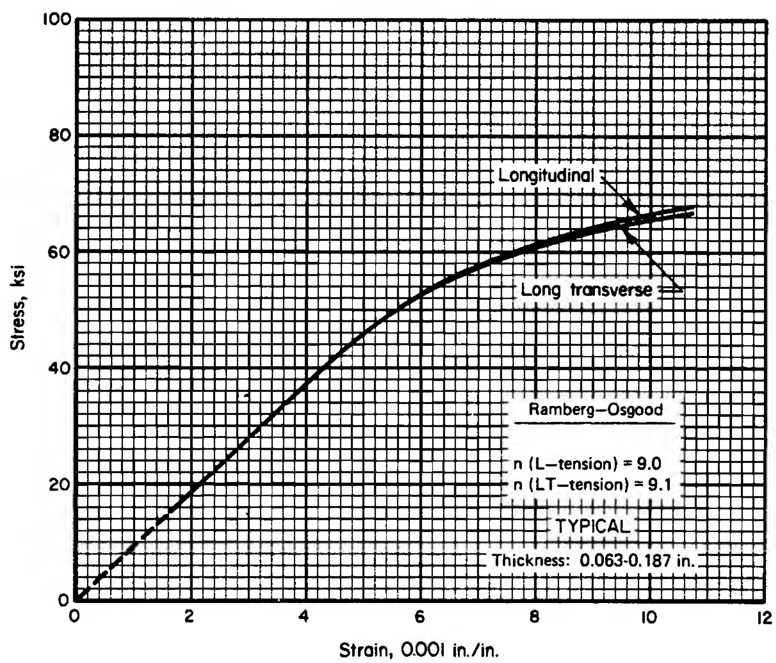

FIGURE 3.7.7.3.6(d). *Typical compressive stress-strain and compressive tangent-modulus curves for clad 7475-T761 aluminum alloy sheet at room temperature.*

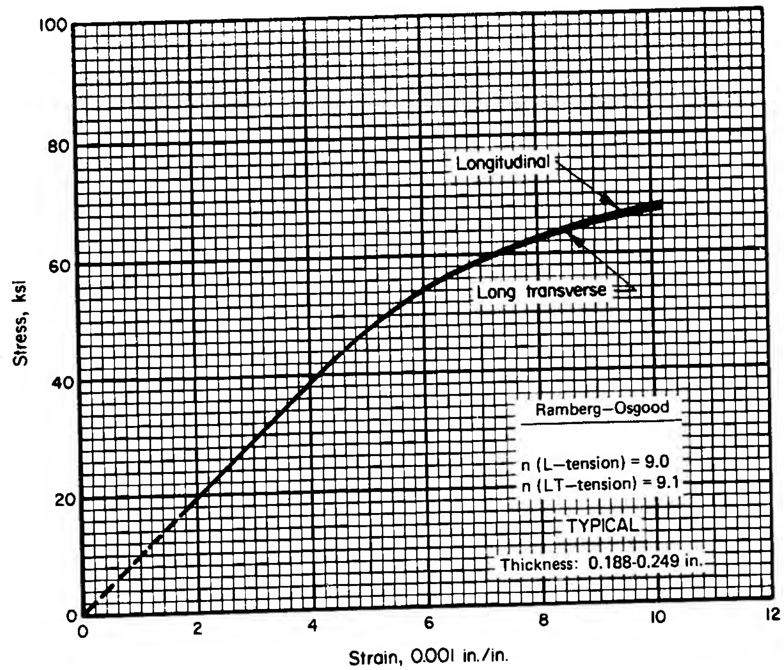

FIGURE 3.7.7.3.6(e). *Typical tensile stress-strain curves for clad 7475-T761 aluminum alloy sheet at room temperature.*

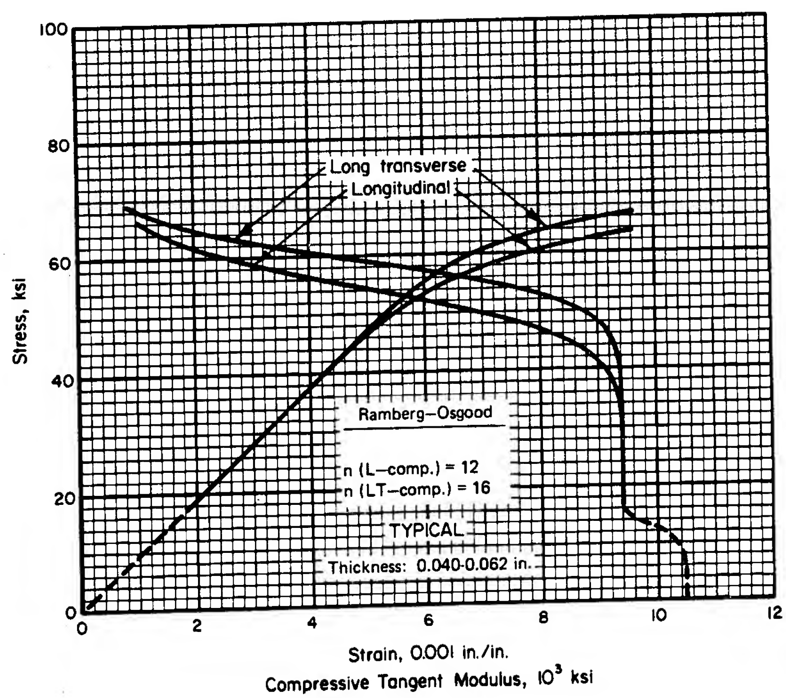

FIGURE 3.7.7.3.6(f). *Typical compressive stress-strain and compressive tangent-modulus curves for clad 7475-T761 aluminum alloy sheet at room temperature.*

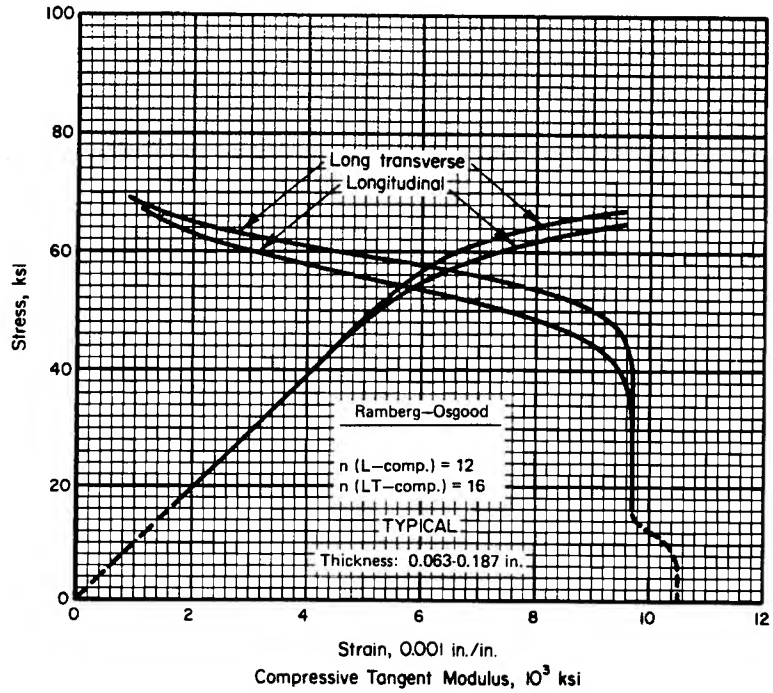

FIGURE 3.7.7.3.6(g). *Typical compressive stress-strain and compressive tangent-modulus curves for clad 7475-T761 aluminum alloy sheet at room temperature.*

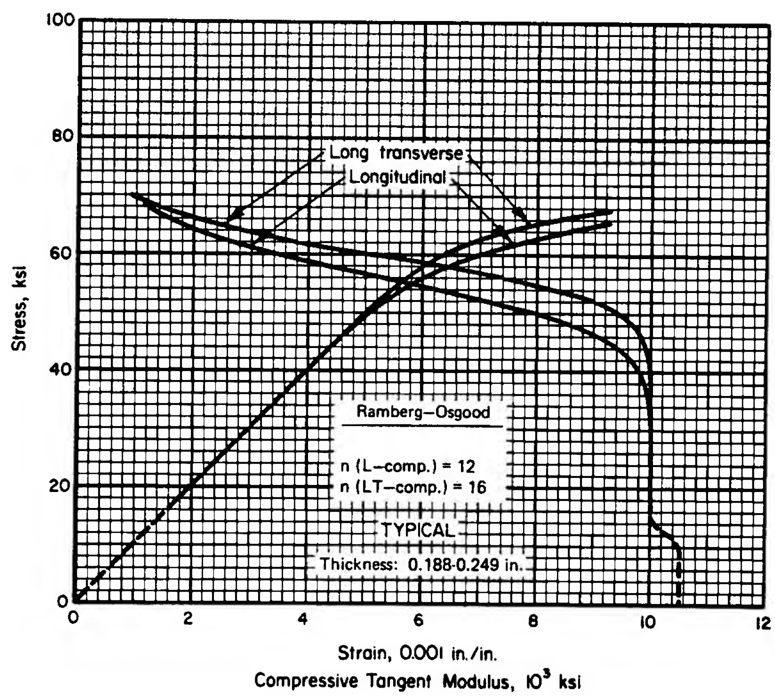

FIGURE 3.7.7.3.6(h). *Typical compressive stress-strain and compressive tangent-modulus curves for clad 7475-T761 aluminum alloy sheet at room temperature.*

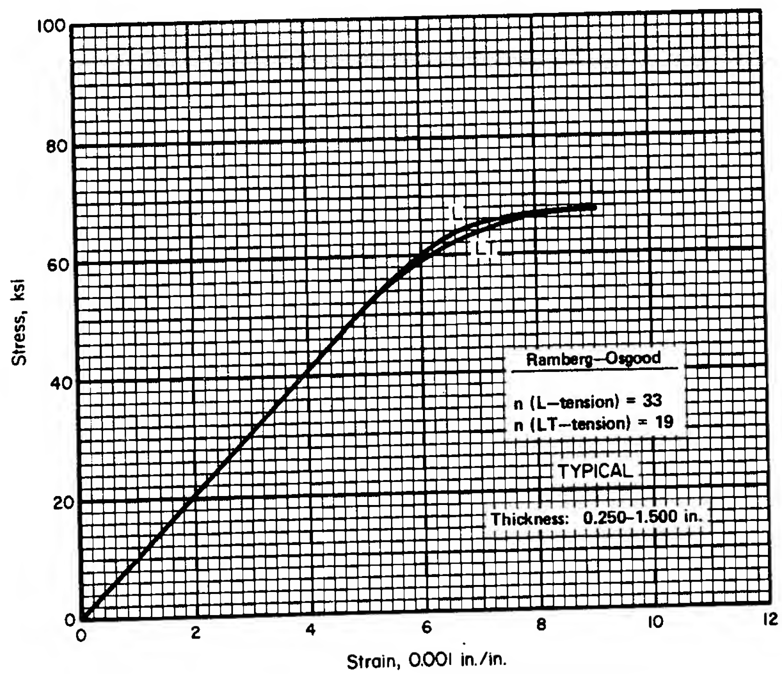

FIGURE 3.7.7.3.6(i). *Typical tensile stress-strain curves for 7475-T7651 aluminum alloy plate at room temperature.*

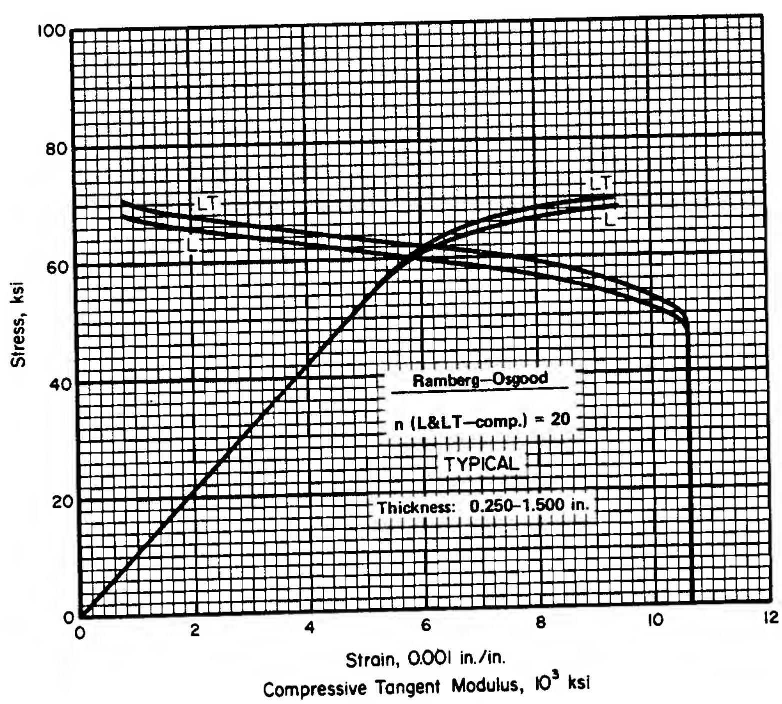

FIGURE 3.7.7.3.6(j). *Typical compressive stress-strain and compressive tangent-modulus curves for 7475-T761 aluminum alloy plate at room temperature.*

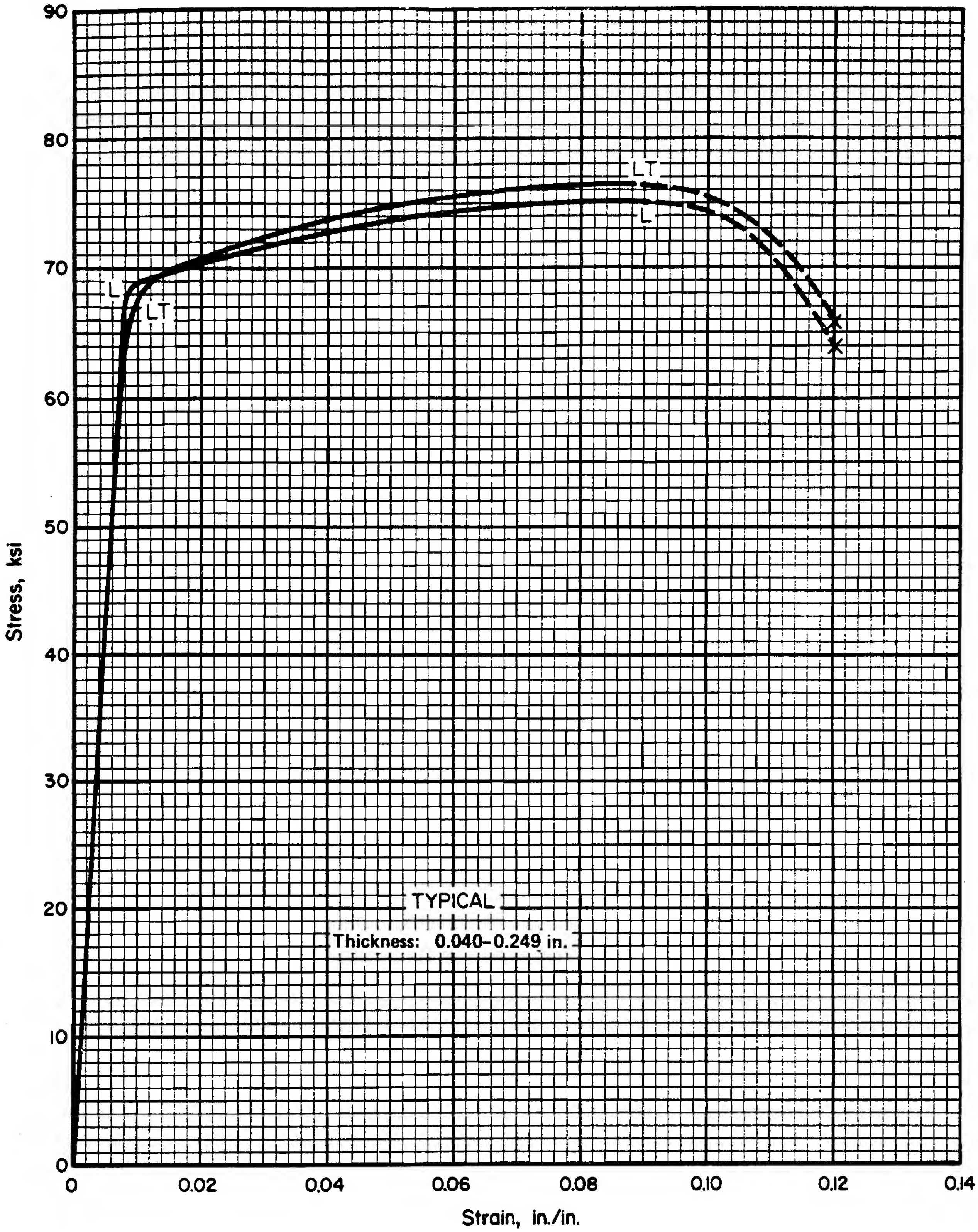

FIGURE 3.7.7.3.6(k). *Typical tensile stress-strain (full range) curves for 7475-T7661 aluminum alloy sheet at room temperature.*

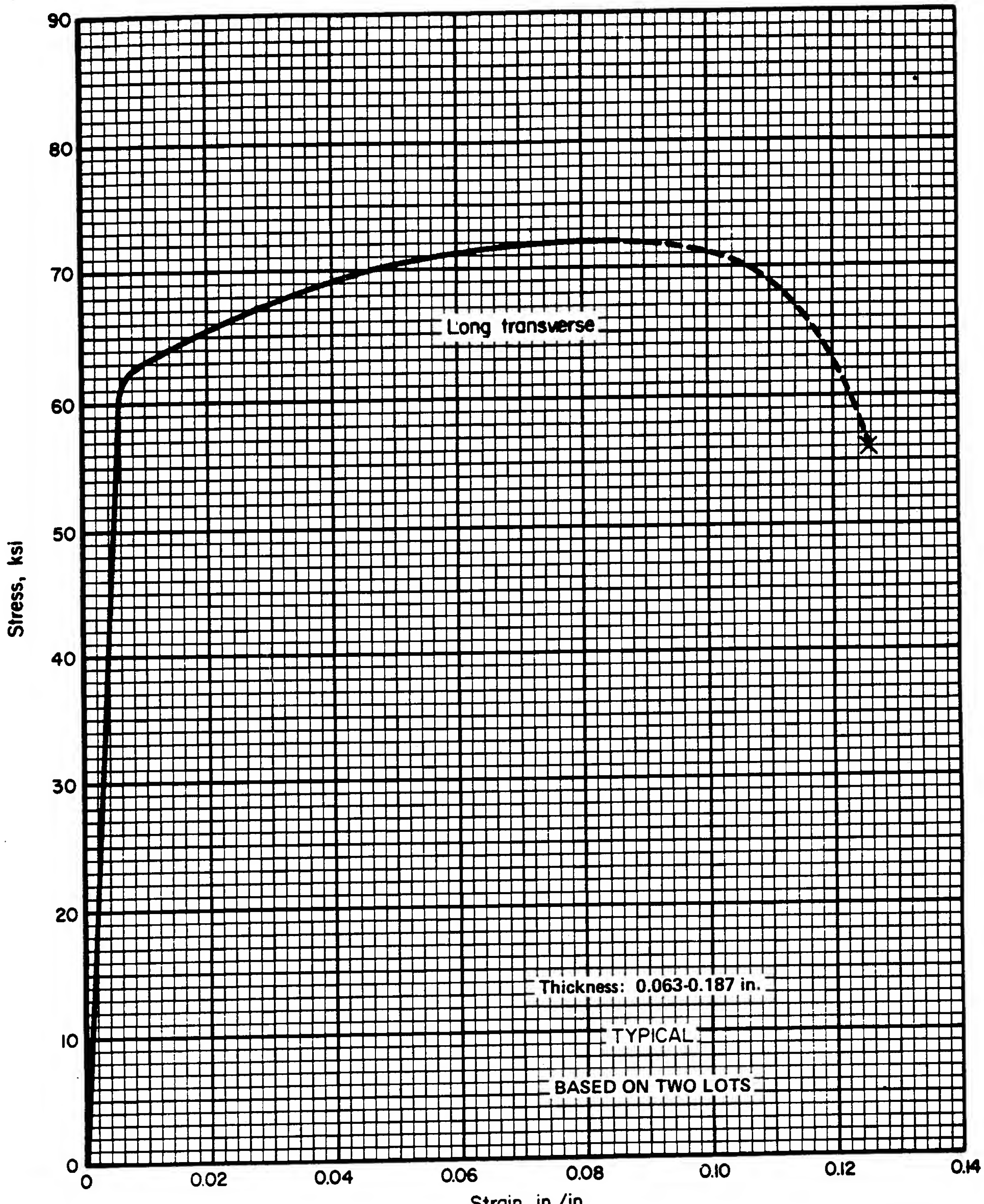

FIGURE 3.7.7.3.6(l). *Typical tensile stress-strain (full range) curves for clad 7475-T7651 aluminum alloy sheet at room temperature.*

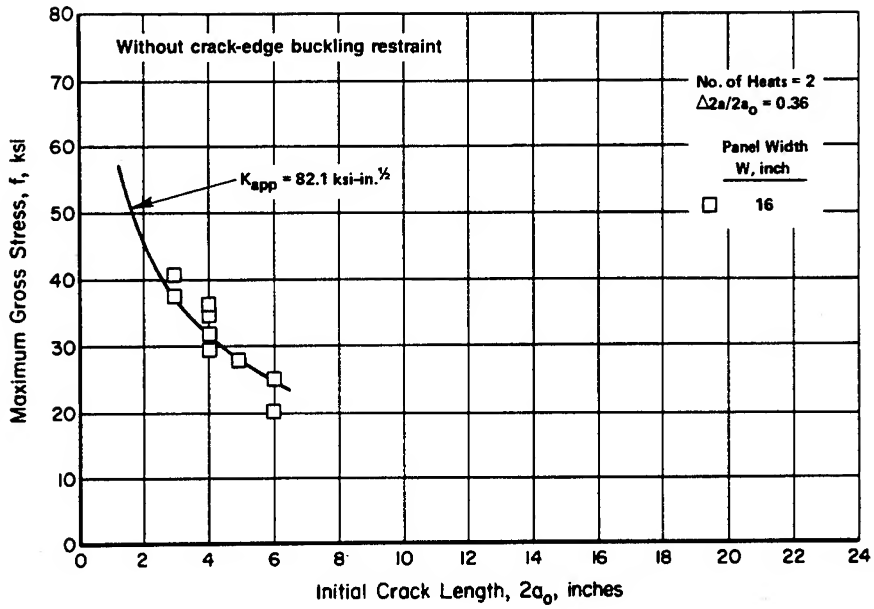

FIGURE 3.7.7.3.10(a). *Residual strength behavior of 0.063-inch-thick 7475-T761 aluminum alloy sheet at room temperature. Crack orientation is L-T. [References 3.1.2.1.6(d) and 3.2.5.1.9(d)].*

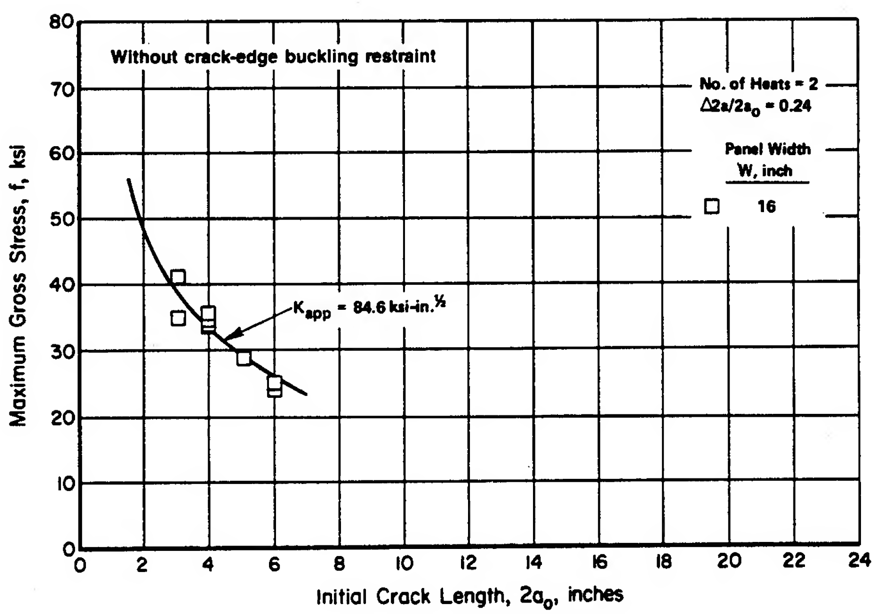

FIGURE 3.7.7.3.10(b). *Residual strength behavior of 0.063-inch-thick 7475-T761 aluminum alloy sheet at room temperature. Crack orientation is T-L. [References 3.1.2.1.6(d) and 3.2.5.1.9(d)].*

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3.8 200.0 Series Cast Alloys

Alloys of the 200 series contain copper as the principal alloying element, and are particularly useful for elevated temperature applications.

3.8.1 A201.0 ALLOY

3.8.1.0 *Comments and Properties.*—A201.0 is a high-strength, heat-treatable Al-Cu-Ag casting alloy. In the T7 (overaged) temper, it possesses high strength, moderate ductility and optimum resistance to stress-corrosion cracking. Refer to Section 3.1.3.4 for comments regarding the weldability of the alloy.

A material specification covering this alloy is presented in Table 3.8.1.0(a). Room-temperature mechanical and physical properties are presented in Table 3.8.1.0(b). The effect of temperature on thermal expansion is shown in Figure 3.8.1.0.

TABLE 3.8.1.0(a). *Material Specification for A201.0 Aluminum Alloy*

Specification	Form
MIL-A-21180	Casting (T7 temper)

The temper index for A201.0 is as follows:

Section	Temper
3.8.1.1	T7

3.8.1.1 *T7 Temper.*—Figure 3.8.1.1.6 presents a typical tensile stress-strain curve. Strain control fatigue data are shown in Figures 3.8.1.1.8(a) through (c).

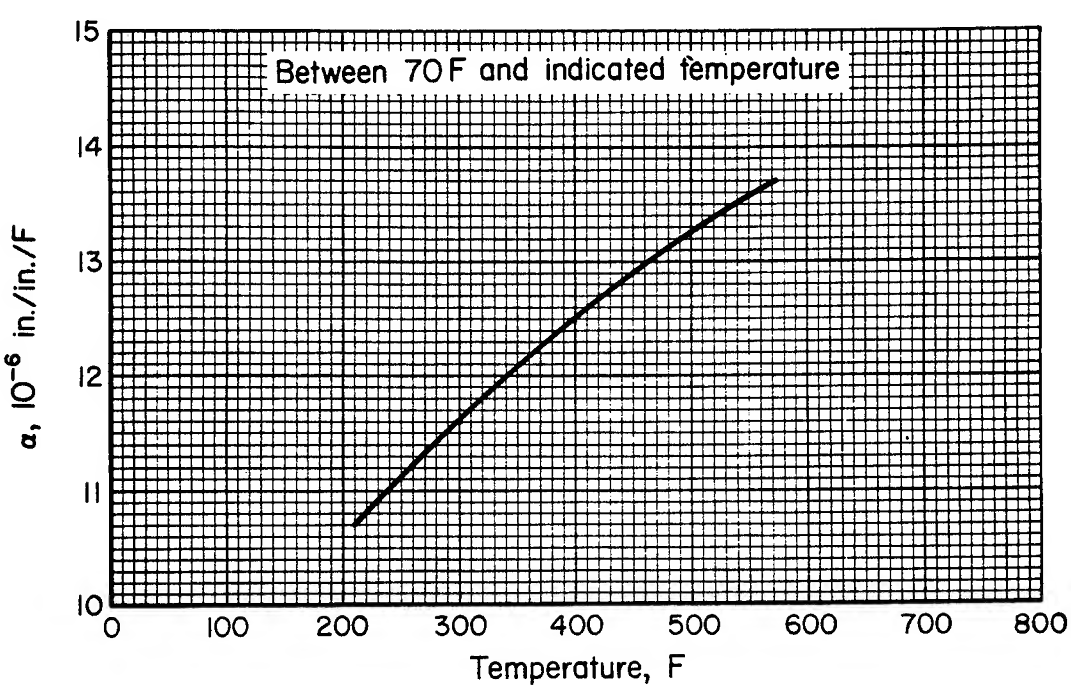


FIGURE 3.8.1.0. *Effect of temperature on the thermal expansion of A201.0 aluminum alloy casting.*

TABLE 3.8.1.0(b). *Design Mechanical and Physical Properties of A201.0 Aluminum Alloy Casting*

Specification	MIL-A-21180			
Form	Casting			
Temper	T7			
Location within casting	Designated area		Nondesignated area	
Strength class number[a]	1	2	10	11
Basis	S	S	S	S
Mechanical Properties[b,c]:				
F_{tu}, ksi:	60	60	60	56
F_{ty}, ksi:	50	50	50	48
F_{cy}, ksi:	51	51	51	49
F_{su}, ksi	36	36	36	34
F_{bru}[d], ksi:				
(e/D = 1.5)	95	95	95	88
(e/D = 2.0)	122	122	122	114
F_{bry}[d], ksi:				
(e/D = 1.5)	74	74	74	71
(e/D = 2.0)	87	87	87	83
e, percent	3	5	3	1.5
E, 10^3 ksi	10.3			
E_c, 10^3 ksi	10.7			
G, 10^3 ksi	4.0			
μ	0.33			
Physical Properties:				
ω, lb/in.^{3}	0.101			
C, Btu/(lb)(F)	0.22 (at 212 F)			
K, Btu/[(hr)(ft^2)(F)/ft]	70 (at 77 F)			
α, 10^{-6} in./in./F	See Figure 3.8.1.0			

[a] The attainable strength class number is dependent on the casting configuration, complexity, and size (both weight and wall thickness). Favorable experience with a particular configuration may allow some foundries to produce to a higher strength class number than others. In case of doubt regarding the strength class number, the designer should consult or negotiate with the foundry to determine the proper strength class number to assign for a specific casting.

[b] For any casting process; i.e., special mold, permanent mold, or sand mold (including chilling).

[c] The mechanical properties shown are reliably obtainable in castings of this alloy and heat-treat condition when produced under the quality assurance provisions of MIL-A-21180. These provisions require preproduction approval, documentation of foundry procedures, and specific destructive and nondestructive testing procedures for the acceptance of each production lot of castings. Strict adherence to these requirements is mandatory if these properties are to be reliably assured in each casting.

[d] Bearing values are "dry pin" values per Section 1.4.7.1.

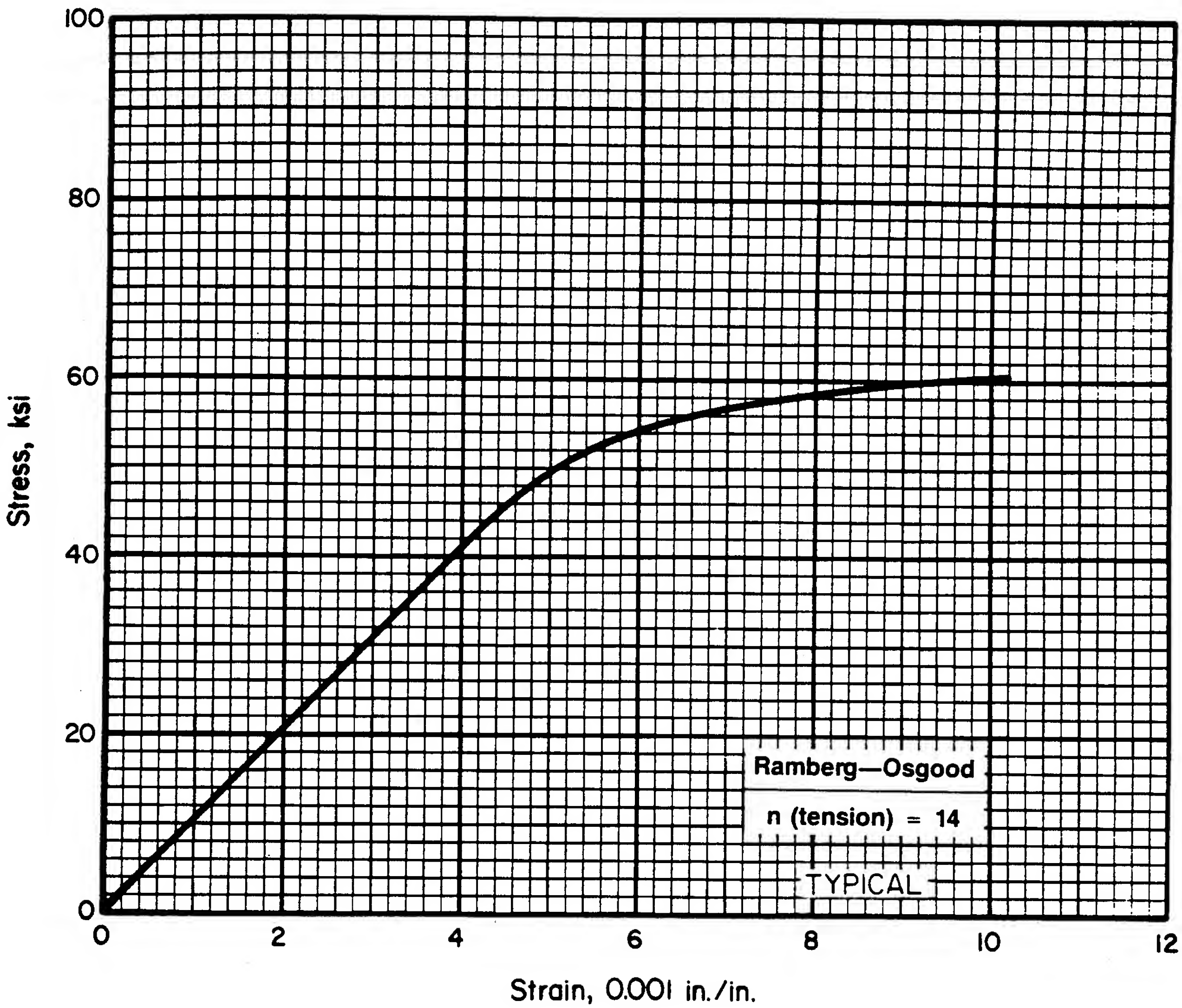


FIGURE 3.8.1.1.6. *Typical tensile stress-strain curve for A201.0-T7 aluminum alloy casting, designated area, at room temperature.*

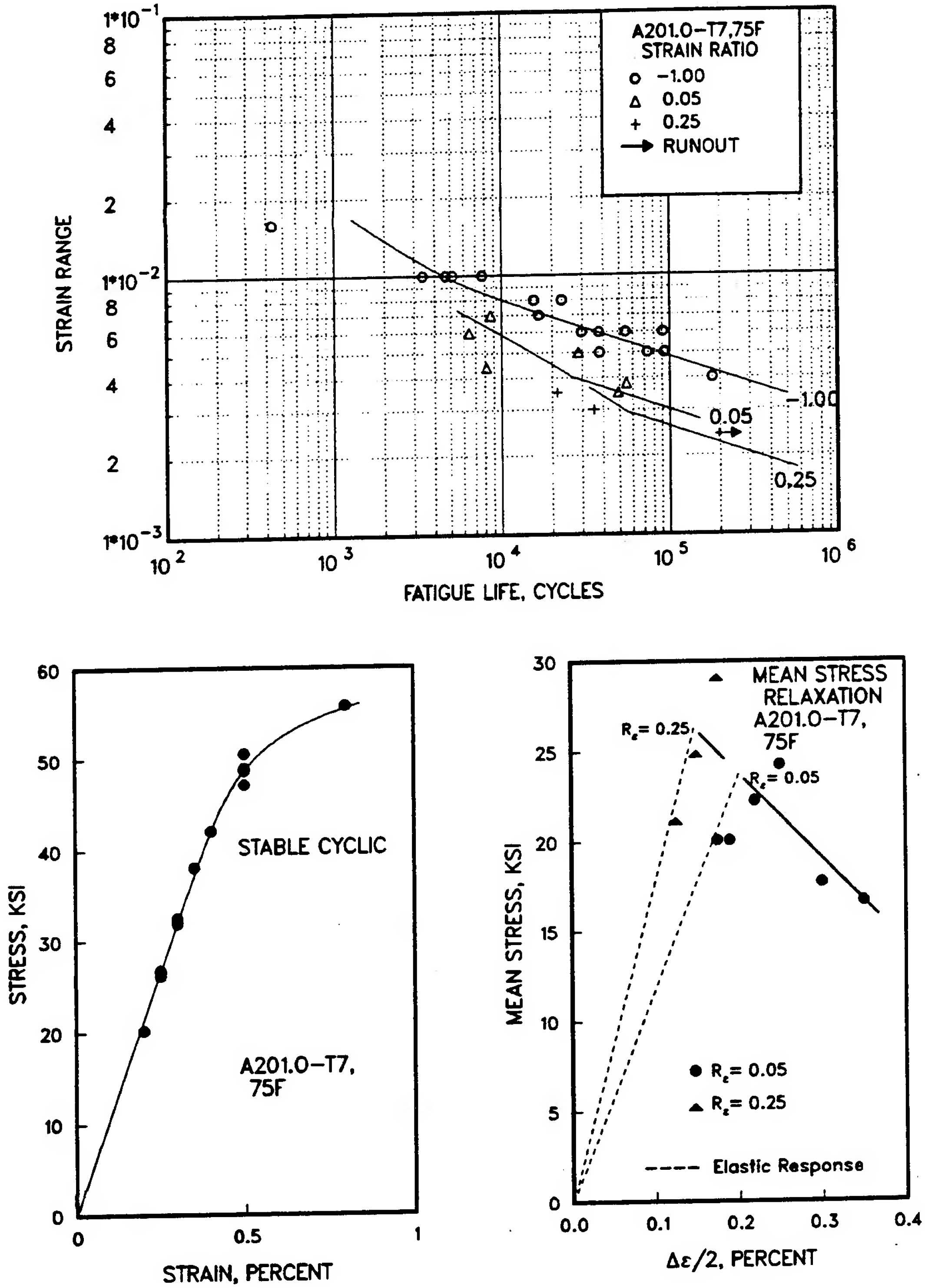


FIGURE 3.8.1.1.8(a). *Best fit ε/N curves, cyclic stress-strain curve, and mean stress relaxation curve for A201.0-T7 casting at 75 F.*

Correlative Information for Figure 3.8.1.1.8(a)

Product Form/Thickness: Casting

Thermal Mechanical Processing History: T7, HIP

Properties:

TUS, ksi	TYS, ksi	E, ksi	Temp., F
57-66	45-57	10,800	75

Stress-Strain Equations:
Cyclic (Companion Specimen)
Proportional Limit = 42 ksi
$(\Delta\sigma/2) = 72(\Delta\varepsilon_p/2)^{0.058}$
Mean Stress Relaxation, ksi
$\sigma_m = 33.3 - 4755(\Delta\varepsilon/2)$

Specimen Details: Uniform gage test section
0.250-inch diameter

Reference: 3.8.1.1.8(a) and (b)

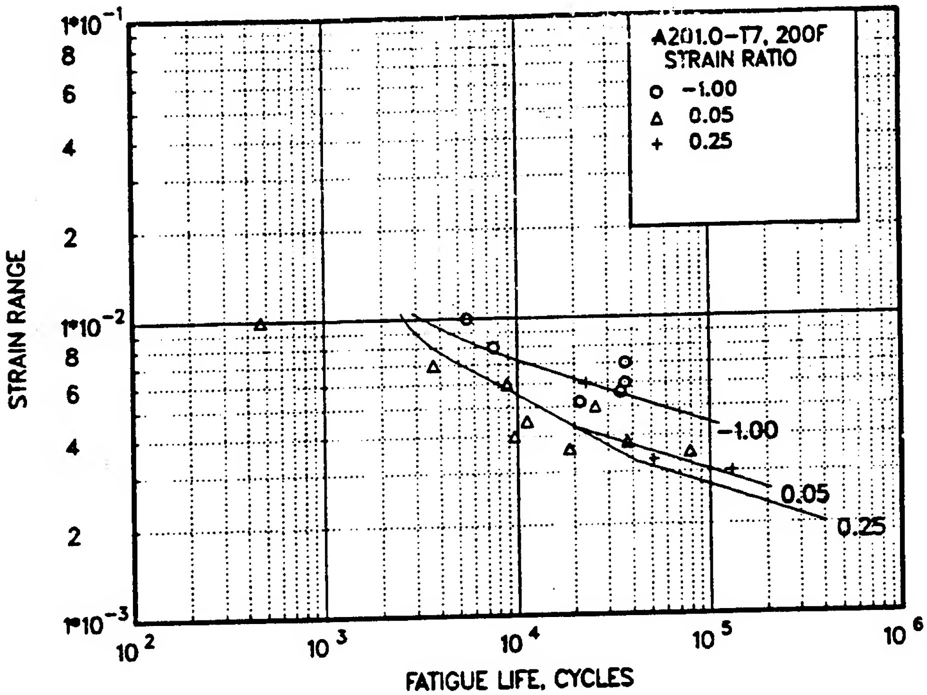
Test Parameters:
Strain Rate/Frequency - 20 cpm
Wave Form - Triangular
Temperature - 75 F
Atmosphere - Air

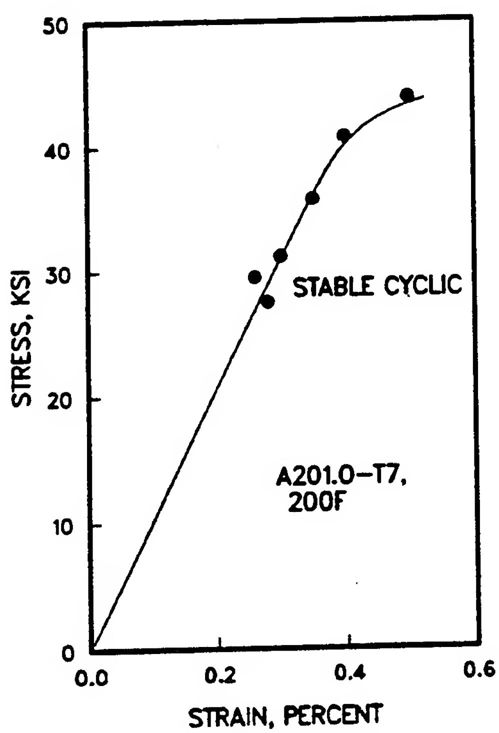
No. of Heats/Lots: 3

Equivalent Strain Equation:
Log $N_f = -6.54-4.60 \log (\varepsilon_{eq})$
$\varepsilon_{eq} = (\Delta\varepsilon)^{0.37} (S_{max}/E)^{0.63}$
Standard Deviation in Log (Life) = 0.242
Adjusted R^2 Statistic: 83%

Sample Size: 26

[Caution: The equivalent strain model may provide unrealistic life predictions for strain ratios and ranges beyond those represented above]





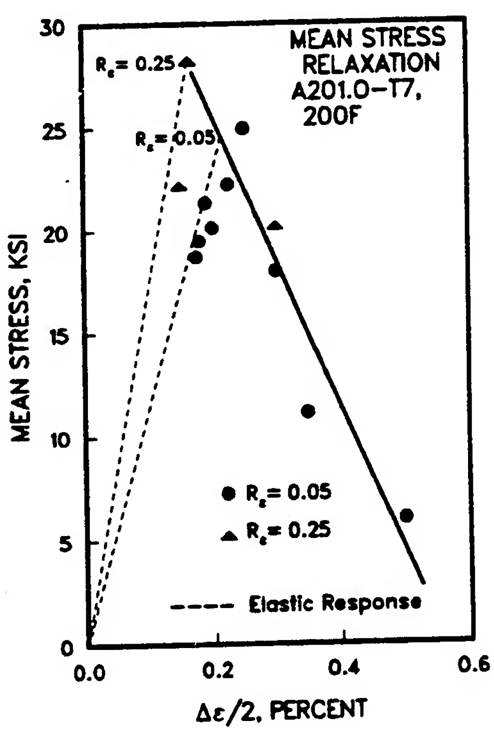


Figure 3.8.1.1(b). *Best fit ε/N curves, cyclic stress-strain curve, and mean stress reduction curve for A201.0-T7 casting at 200 F.*

Correlative Information for Figure 3.8.1.1.8(b)

Product Form/Thickness: Casting

Thermal Mechanical Processing History: T7, HIP

Properties:

TUS, ksi	TYS, ksi	E, ksi	Temp., F
53-59	47-55	10,339	200

Stress-Strain Equations:
Cyclic (Companion Specimen)
Proportional Limit = 39 ksi
$(\Delta\sigma/2) = 58(\Delta\varepsilon_p/2)^{0.041}$
Mean Stress Relaxation, ksi
$\sigma_m = 39.7 - 7049(\Delta\varepsilon/2)$

Specimen Details: Uniform gage test section
0.250-inch diameter

Reference: 3.8.1.1.8(a)

Test Parameters:
Strain Rate/Frequency - 20 cpm
Wave Form - Triangular
Temperature - 200 F
Atmosphere - Air

No. of Heats/Lots: 3

Equivalent Strain Equation:
$\text{Log } N_f = -6.68 - 4.66 \log (\varepsilon_{eq})$
$\varepsilon_{eq} = (\Delta\varepsilon)^{0.50} (S_{max}/E)^{0.50}$
Standard Deviation in Log (Life) = 0.359
Adjusted R^2 Statistic: 59%

Sample Size: 18

[Caution: The equivalent strain model may provide unrealistic life predictions for strain ratios and ranges beyond those represented above]

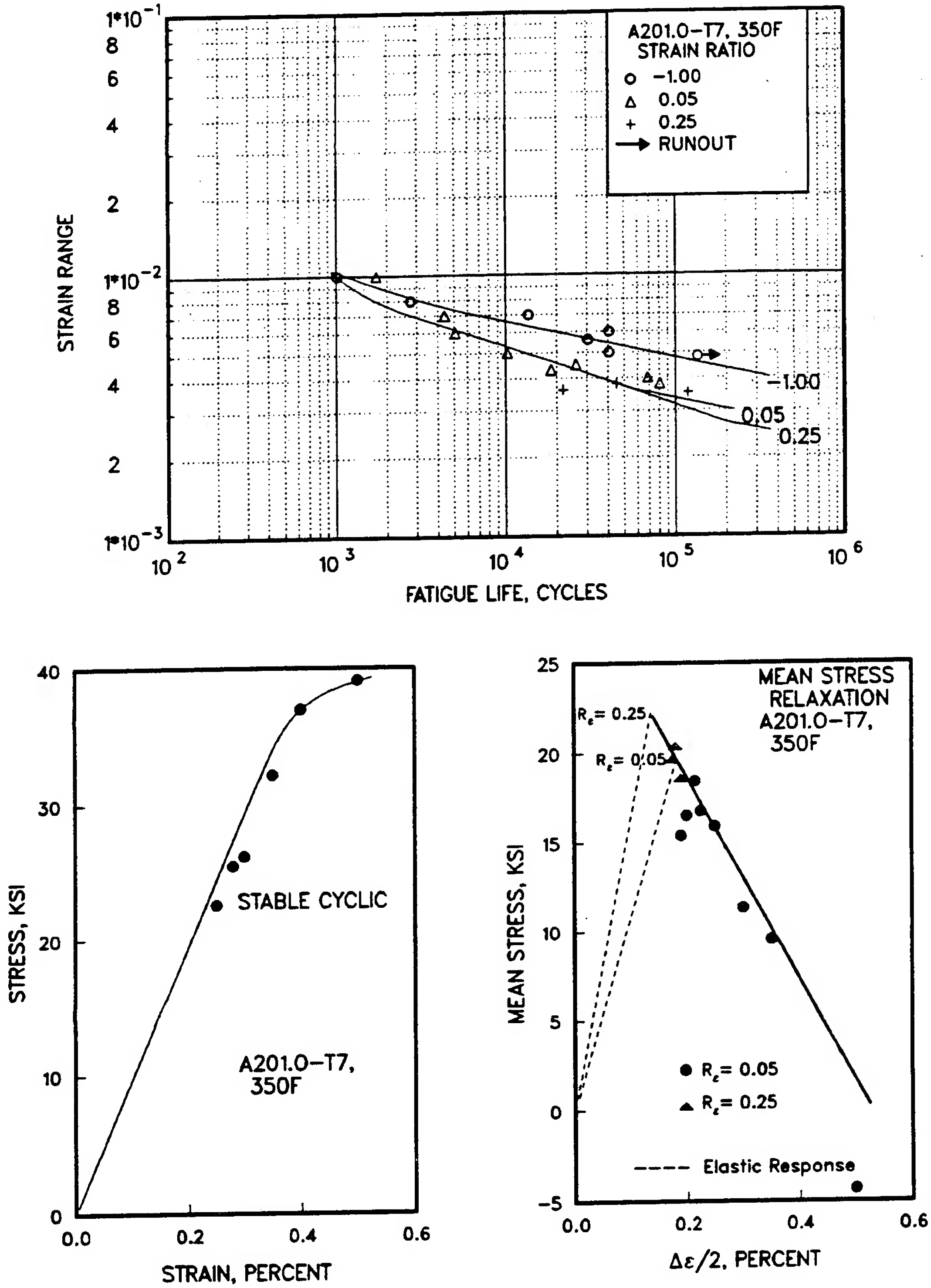


FIGURE 3.8.1.1.8(c). *Best fit ε/N curves, cyclic stress-strain curve, and mean stress relaxation curve for A201.0-T7 casting at 350 F.*

Correlative Information for Figure 3.8.1.1.8(c)

Product Form/Thickness: Casting

Thermal Mechanical Processing History: T7, HIP

Properties:

TUS, ksi	TYS, ksi	E, ksi	Temp., F
48-53	40-48	9783	350

Stress-Strain Equations:
Cyclic (Companion Specimen)
Proportional Limit = 36 ksi
$(\Delta\sigma/2) = 50(\Delta\varepsilon_p/2)^{0.036}$
Mean Stress Relaxation, ksi
$\sigma_m = 30.0 - 5664(\Delta\varepsilon/2)$

Specimen Details: Uniform gage test section 0.250-inch diameter

Reference: 3.8.1.1.8(a)

Test Parameters:
Strain Rate/Frequency - 20 cpm
Wave Form - Triangular
Temperature - 350 F
Atmosphere - Air

No. of Heats/Lots: 3

Equivalent Strain Equation:
$\text{Log } N_f = -12.44-7.07 \log (\varepsilon_{eq})$
$\varepsilon_{eq} = (\Delta\varepsilon)^{0.52} (S_{max}/E)^{0.48}$
Standard Deviation in Log (Life) = 0.000817 $(1/\varepsilon_{eq})$
Adjusted R^2 Statistic: 93%

Sample Size: 18

[Caution: The equivalent strain model may provide unrealistic life predictions for strain ratios and ranges beyond those represented above]

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3.9 300.0 Series Cast Alloys

Casting alloys of the 300.0 series contain silicon with added copper and/or magnesium as the principal alloying elements. They are heat treatable. Because of the high silicon content, they are among the easiest to cast by a variety of techniques. They have high resistance to corrosion.

3.9.1 354.0 ALLOY

3.9.1.0 *Comments and Properties.*—354.0 is a heat-treatable Al-Si-Mg alloy being among the highest strength of commercial casting alloys. It has good casting characteristics; however, its use is generally restricted to permanent mold castings. Refer to Section 3.1.3.4 for comments regarding the weldability.

A material specification for 354.0 aluminum alloy is presented in Table 3.9.1.0(a). Room-temperature mechanical and physical properties are shown in Table 3.9.1.0(b).

TABLE 3.9.1.9(a). *Material Specifications for 354.0 Aluminum Alloy*

Specification	Form
MIL-A-21180	Casting

TABLE 3.9.1.0(b). *Design Mechanical and Physical Properties of 354.0 Aluminum Alloy Casting*

Specification	MIL-A-21180			
Form	Casting			
Temper	T6			
Location within casting	Designated area		Nondesignated area	
Strength class number[a]	1	2	10	11
Basis	S	S	S	S
Mechanical Properties[b,c]:				
F_{tu}, ksi	47	50	47	43
F_{ty}, ksi	36	42	36	33
F_{cy}, ksi	36	42	36	33
F_{su}, ksi	29	31	29	27
F_{bru}, ksi:				
(e/D = 1.5)	81	86	81	74
(e/D = 2.0)	101	107	101	92
F_{bry}, ksi:				
(e/D = 1.5)	57	66	57	52
(e/D = 2.0)	67	78	67	62
e, percent	3	2	3	2
E, 10^3 ksi	10.6			
E_c, 10^3 ksi	10.8			
G, 10^3 ksi	4.0			
μ	0.33			
Physical Properties:				
ω, lb/in.^{3}	0.098			
C, Btu/(lb)(F)	0.23 (at 212 F)			
K, Btu/[(hr)(ft^2)(F)/ft]	...			
α, 10^{-6} in./in./F	1.6 (68 to 212 F)			

[a] The attainable strength class number is dependent on the casting configuration, complexity, and size (both weight and wall thickness). Favorable experience with a particular configuration may allow some foundries to produce to a higher strength class number than others. In case of doubt regarding the strength class number, the designer should consult or negotiate with the foundry to determine the proper strength class number to assign for a specific casting.

[b] For any casting process; i.e., special mold, permanent mold, or sand mold (including chilling).

[c] The mechanical properties shown are reliably obtainable in castings of this alloy and heat-treat condition when produced under the quality assurance provisions of MIL-A-21180. These provisions require preproduction approval, documentation of foundry procedures, and specific destructive and nondestructive testing procedures for the acceptance of each production lot of castings. Strict adherence to these requirements is mandatory if these properties are to be reliably assured in each casting.

3.9.2 355.0 ALLOY

3.9.2.0 *Comments and Properties.*—355.0 is a heat-treatable Al-Si-Mg alloy that is readily cast and has good pressure tightness. Refer to Section 3.1.3.4 for comments regarding the weldability of the alloy.

A material specification for 355.0 aluminum alloy is presented in Table 3.9.2.0(a). Room-temperature mechanical and physical properties are shown in Table 3.9.2.0(b). The effect of temperature on thermal expansion is shown in Figure 3.9.2.0.

TABLE 3.9.2.0(a). *Material Specification for 355.0 Aluminum Alloy*

Specification	Form
AMS 4281	Permanent mold casting

TABLE 3.9.2.0(b). *Design Mechanical and Physical Properties of 355.0 Aluminum Alloy*

Specification	AMS 4281
Form	Permanent mold casting
Temper	T6
Location within casting	As specified
Basis	S
Mechanical Properties:	
F_{tu}, ksi	27[a]
F_{ty}, ksi	17[a]
F_{cy}, ksi	17
F_{su}, ksi	17
F_{bru}, ksi:	
(e/D = 1.5)	46
(e/D = 2.0)	58
F_{bry}, ksi:	
(e/D = 1.5)	27
(e/D = 2.0)	32
e, percent	0.4[a]
E, 10^3 ksi	10.3
E_c, 10^3 ksi	10.3
G, 10^3 ksi	3.8
μ	0.33
Physical Properties:	
ω, lb/in.^{3}	0.098
C, Btu/(lb)(F)	0.23 (at 212 F)
K, Btu/[(hr)(ft^2)(F)/ft]	88 (at 77 F)
α, 10^{-6} in./in./F	See Figure 3.9.2.0

[a]Conformance to tensile property requirements is determined by testing specimens cut from casting only when specified on drawing.

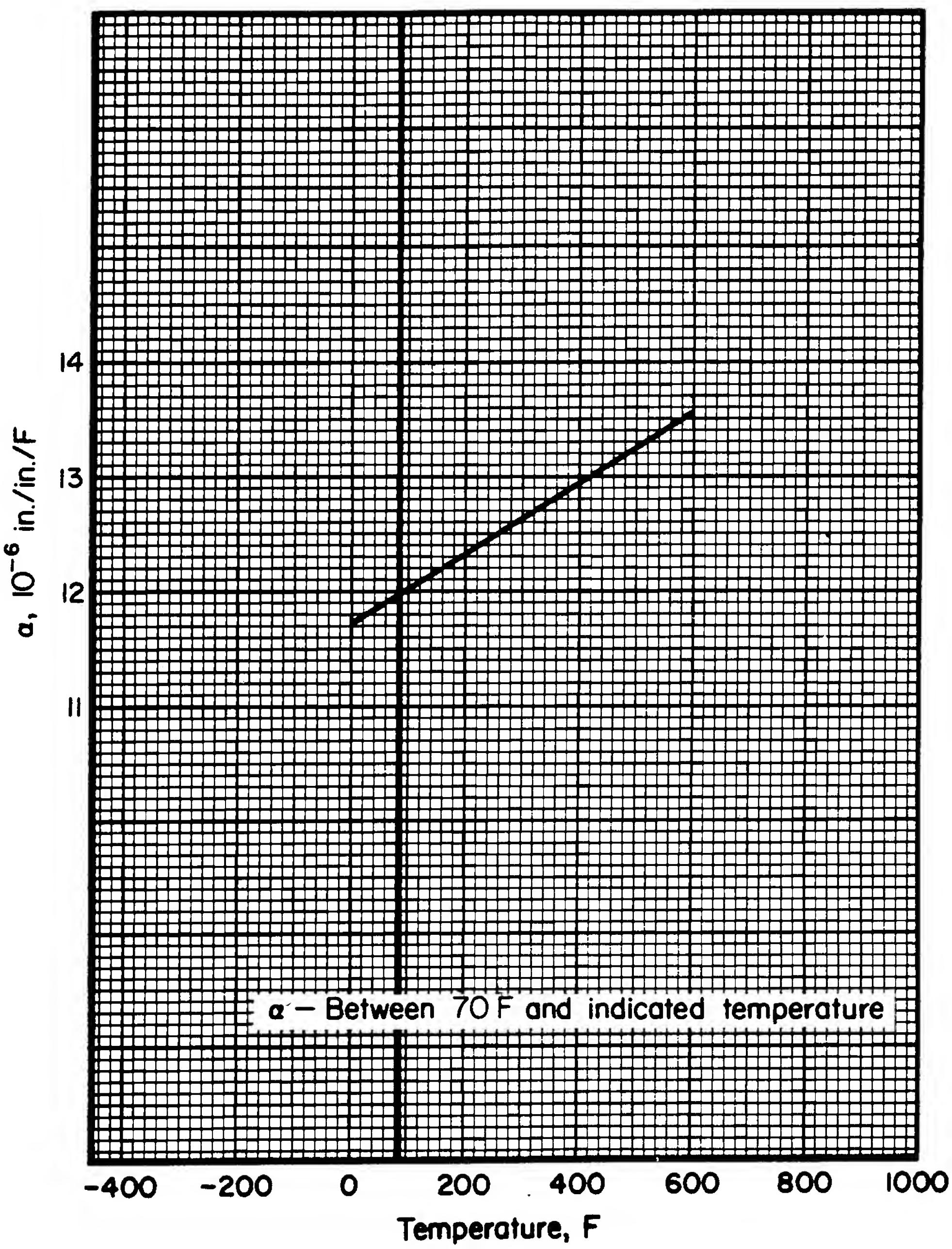

FIGURE 3.9.2.0. *Effect of temperature on the thermal expansion of 355.0 aluminum alloy casting.*

3.9.3 C355.0 Alloy

3.9.3.0 *Comments and Properties.*—C355.0 is an Al-Si-Mg alloy similar to 355.0 but has impurities controlled to lower limits resulting in higher strengths. It has good casting characteristics. Refer to Section 3.1.3.4 for comments regarding the weldability of the alloy.

A material specification for C355.0 aluminum alloy is presented in Table 3.9.3.0(a).

Room-temperature mechanical and physical properties are shown in Table 3.9.3(b).

TABLE 3.9.3.0(a). *Material Specification for C355.0 Aluminum Alloy*

Specification	Form
MIL-A-21180	Casting

TABLE 3.9.3.0(b). *Design Mechanical and Physical Properties of C355.0 Aluminum Alloy Casting*

Specification	MIL-A-21180					
Form	Casting					
Location within casting	T6					
Strength class number[a]	1	2	3	10	11	12
Basis	S	S	S	S	S	S
Mechanical Properties[b,c]:						
F_{tu}, ksi	41	44	50	41	37	35
F_{ty}, ksi	31	33	40	31	30	28
F_{cy}, ksi	31	33	40	31	30	28
F_{su}, ksi	26	28	31	26	23	22
F_{bru}, ksi:						
(e/D = 1.5)	70	75	86	70	63	60
(e/D = 2.0)	88	94	107	88	79	75
F_{bry}, ksi:						
(e/D = 1.5)	49	52	63	49	47	44
(e/D = 2.0)	58	62	75	58	59	52
e, percent	3	3	2	3	1	1
E, 10^3 ksi	10.1					
E_c, 10^3 ksi	10.3					
G, 10^3 ksi	3.85					
μ	0.33					
Physical Properties:						
ω, lb/in.^{3}	0.098					
C, Btu/(lb)(F)	0.23 (at 212 F)					
K, Btu/[(hr)(ft^2)(F)/ft]	88 (at 77 F)					
α, 10^{-6} in./in./F	12.4 (68 to 212 F)					

[a]The attainable strength class number is dependent on the casting configuration, complexity, and size (both weight and wall thickness). Favorable experience with a particular configuration may allow some foundries to produce a higher strength class number than others. In case of doubt regarding the strength class number, the designer should consult or negotiate with the foundry to determine the proper strength class number to assign for a specific casting.
[b]For any casting process; i.e., special mold, permanent mold, or sand mold (including chilling).
[c]The mechanical properties shown are reliably obtainable in castings of this alloy and heat-treat condition when produced under the quality assurance provisions of MIL-A-21180. These provisions require preproduction approval, documentation of foundry procedures, and specific destructive and nondestructive testing procedures for the acceptance of each production lot of castings. Strict adherence to these requirements is mandatory if these properties are to be reliably assured in each casting.

3.9.4 356.0 ALLOY

3.9.4.0 *Comments and Properties.*—356.0 is among the easiest of alloys to cast by a variety of techniques. It is heat treatable, has intermediate strengths, and has high resistance to corrosion. Refer to Section 3.1.3.4 for comments regarding the weldability of the alloy.

Material specifications for 356.0 aluminum alloy are presented in Table 3.9.4.0(a). Room-temperature mechanical and physical properties are shown in Table 3.9.4.0(b). The effect of temperature on thermal expansion is given in Figure 3.9.4.0.

TABLE 3.9.4.0(a). *Materials Specifications for 356.0 Aluminum Alloy*

Specification	Form
AMS 4284	Permanent mold casting
AMS 4217	Sand casting
AMS 4260	Investment casting

TABLE 3.9.4.0(b). *Design Mechanical and Physical Properties of 356.0 Aluminum Alloy*

Specification	AMS 4217	AMS 4260	AMS 4284
Form	Sand casting	Investment casting	Permanent mold casting
Temper	T6	T6	T6
Location within casting	Thick and thin areas	As specified	As specified
Basis	S	S	S
Mechanical Properties:			
F_{tu}, ksi	22[a,b]	25[a]	25[a]
F_{ty}, ksi	15[a,b]	16[a]	16[a]
F_{cy}, ksi	15	16	16
F_{su}, ksi	14	16	16
F_{bru}, ksi:			
(e/D = 1.5)	38	43	43
(e/D = 2.0)	47	53	53
F_{bry}, ksi:			
(e/D = 1.5)	24	25	25
(e/D = 2.0)	28	30	30
e, percent	0.7[a,b]	1[a]	0.7[a]
E, 10^3 ksi		10.3	
E_c, 10^3 ksi		10.3	
G, 10^3 ksi		3.85	
μ		0.33	
Physical Properties:			
ω, lb/in.^{3}		0.097	
C, Btu/(lb)(F)		0.23 (at 212 F)	
K, Btu/[(hr)(ft^2)(F)/ft]		88 (at 77 F)	
α, 10^{-6} in./in./F		See Figure 3.9.4.0	

[a]Conformance to tensile property requirements is determined by testing specimens cut from casting only when specified on drawing.
[b]Not minimum values, but based upon average of not less than four specimens.

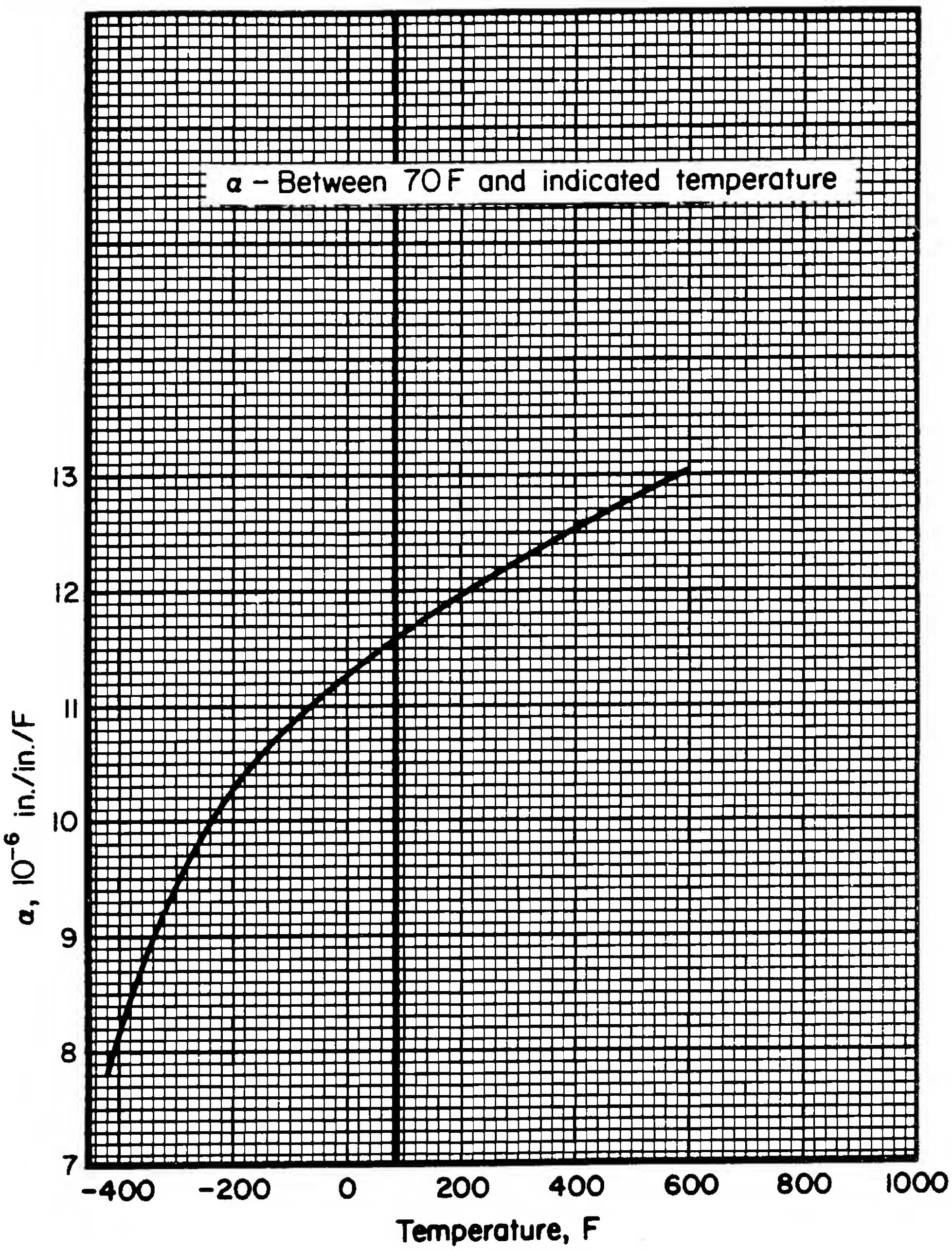

FIGURE 3.9.4.0. *Effect of temperature on the thermal expansion of 356.0 aluminum alloy casting.*

3.9.5 A356.0 ALLOY

3.9.5.0 *Comments and Properties.*—A356.0 is an Al-Si-Mg alloy similar to 356.0, but with impurities controlled to lower limits resulting in higher strengths and ductility. It has good casting characteristics and high resistance to corrosion. Refer to 3.1.3.4 for comments regarding the weldability of the alloy.

Material specifications for A356.0 aluminum alloy are presented in Table 3.9.5.0(a). Room-temperature mechanical and physical properties are shown in Tables 3.9.5.0(b) and (c).

TABLE 3.9.5.0(a). *Material Specifications for A356.0 Aluminum Alloy*

Specification	Form
MIL-A-21180	Casting
AMS 4218	Casting

The temper index for A356.0 is as follows:

Section	Temper
3.9.5.1	T6P
3.9.5.2	T6

3.9.5.1 *T6P Temper.*—Tensile stress-strain and full-range stress-strain curves at room temperature are presented in Figures 3.9.5.1.6(a) and (b), respectively.

TABLE 3.9.5.0(b). *Design Mechanical and Physical Properties of A356.0 Aluminum Alloy Casting*

Specification	MIL-A-21180					
Form	Casting					
Temper	T6					
Location within casting	Designated area			Nondesignated area		
Strength class number[a]	1	2	3	10	11	12
Basis	S	S	S	S	S	S
Mechanical Properties[b,c]:						
F_{tu}, ksi	38	40	45	38	33	32
F_{ty}, ksi	28	30	34	28	27	22
F_{cy}, ksi	28	30	34	28	27	22
F_{su}, ksi	24	25	28	24	21	20
F_{bru}, ksi:						
(e/D = 1.5)	65	69	77	65	57	55
(e/D = 2.0)	81	86	96	81	71	68
F_{bry}, ksi:						
(e/D = 1.5)	44	47	54	44	43	35
(e/D = 2.0)	52	56	63	52	50	41
e, percent	5	3	3	5	3	2
E, 10^3 ksi	10.4					
E_c, 10^3 ksi	10.5					
G, 10^3 ksi	3.9					
μ	0.33					
Physical Properties:						
ω, lb/in.^{3}	0.097					
C, Btu/(lb)(F)	0.23 (at 212 F)					
K, Btu/[(hr)(ft^2)(F)/ft]	88 (at 77 F)					
α, 10^{-6} in./in./F	See Figure 3.9.4.0					

[a]The attainable strength class number is dependent on the casting configuration, complexity, and size (both weight and wall thickness). Favorable experience with a particular configuration may allow some foundries to produce a higher strength class number than others. In case of doubt regarding the strength class number, the designer should consult or negotiate with the foundry to determine the proper strength class number to assign for a specific casting.
[b]For any casting process; i.e., special mold, permanent mold, or sand mold (including chilling).
[c]The mechanical properties shown are reliably obtainable in castings of this alloy and heat-treat condition when produced under the quality assurance provisions of MIL-A-21180. These provisions require preproduction approval, documentation of foundry procedures, and specific destructive and nondestructive testing procedures for the acceptance of each production lot of castings. Strict adherence to these requirements is mandatory if these properties are to be reliably assured in each casting.

TABLE 3.9.5.0(c). *Design and Physical Properties of A356.0 Aluminum Alloy Casting*

Specification	AMS 4218
Form	Sand, investment, permanent mold, and composite castings
Temper	T6P[a]
Location within casting	Any
Basis	S
Mechanical Properties:[b]	
F_{tu}, ksi	32
F_{ty}, ksi	22
F_{cy}, ksi	22
F_{su}, ksi	20
F_{bru}, ksi:	
(e/D = 1.5)	55
(e/D = 2.0)	68
F_{bry}, ksi:	
(e/D = 1.5)	35
(e/D = 2.0)	41
e, percent	2
E, 10^3 ksi	10.4
E_c, 10^3 ksi	10.5
G, 10^3 ksi	3.9
μ	0.33
Physical Properties:	
ω, lb/in.^{3}	0.097
C, Btu/(lb)(F)	0.23 (at 212 F)
K Btu/[(hr)(ft^2)(F)/ft]	88 (at 77 F)
α, 10^{-6} in./in./F	See Figure 3.9.4.0

[a]The letter, P, indicates a variation compared to the standard heat treatment procedure of this temper and/or a difference in the minimum tensile property requirements compared to the Aluminum Association's registered limits.

[b]The mechanical properties shown are reliably obtainable when produced under the quality assurance provisions of AMS 4218. These procedures require radiographic control and specific destructive testing for acceptance of each production lot. Strict adherence to these requirements is mandatory if these properties are to be reliably assured in each casting.

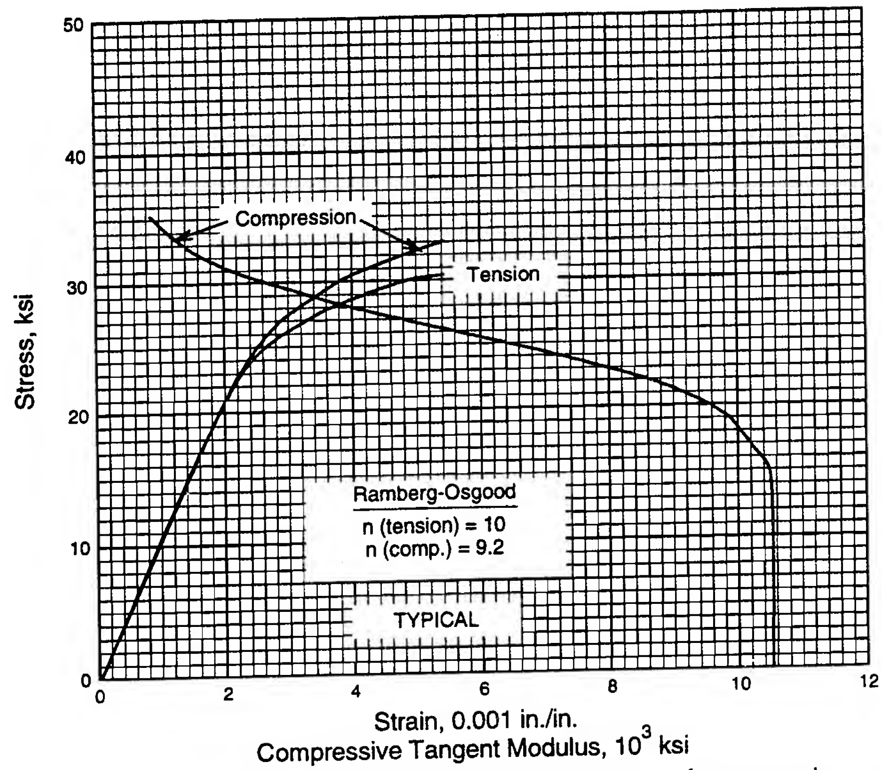

FIGURE 3.9.5.1.6(a). *Typical tensile and compressive stress-strain and compressive tangent-modulus curves for A356.0-T6P aluminum alloy casting at room temperature.*

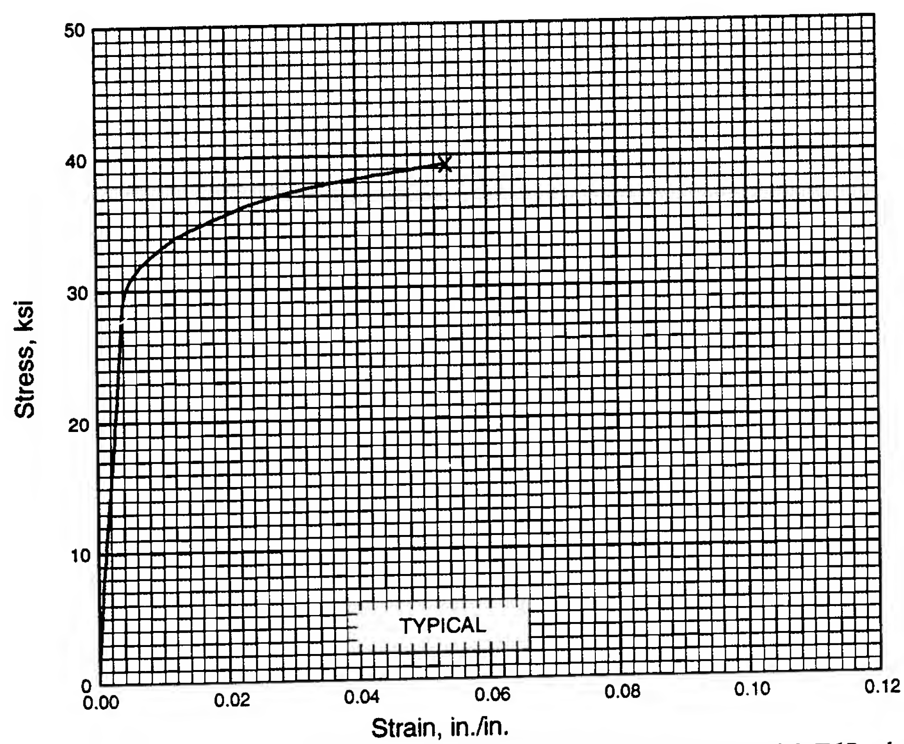

FIGURE 3.9.5.1.6(b). *Typical tensile stress-strain (full-range) curve for A356.0-T6P aluminum alloy casting at room temperature.*

3.9.6 A357.0 ALLOY

3.9.6.0 *Comments and Properties.*—A357.0 is a heat-treatable Al-Si-Mg alloy generally used for permanent mold and premium quality castings in which special properties are developed by careful control of casting and chilling techniques. It has excellent casting characteristics, is heat treatable, and provides high strength, together with good toughness. The alloy also has excellent corrosion resistance. Refer to Section 3.1.3.4 for comments regarding the weldability of the alloy.

A material specification for A357.0 aluminum alloy is presented in Table 3.9.6.0(a). Room-temperature mechanical and physical properties are shown in Table 3.9.6.0(b).

TABLE 3.9.6.0(a). *Material Specification for A357.0 Aluminum Alloy*

Specification	Form
MIL-A-21180	Casting

The temper index for A357.0 is as follows:

Section	Temper
3.9.6.1	T6

3.9.6.1 *T6 Temper.*—Figure 3.9.6.1.6 presents a typical tensile stress-strain curve.

TABLE 3.9.6.0(b). *Design Mechanical and Physical Properties of A357.0 Aluminum Alloy Casting*

Specification	MIL-A-21180				
Form	Casting[b]				
Temper	T6				
Location within casting	Designated area		Nondesignated area		
Strength class number[a]	1	2	10	11	12
Basis	S	S	S	S	S
Mechanical Properties:[c]					
F_{tu}, ksi	45	50	38	41	45
F_{ty}, ksi	35	40	28	31	35
F_{cy}, ksi	35	40	28	31	35
F_{su}, ksi	28	31	24	26	28
F_{bru}[d], ksi:					
(e/D = 1.5)	77	86	65	70	77
(e/D = 2.0)	96	107	81	88	96
F_{bry}[d], ksi:					
(e/D = 1.5)	55	63	44	49	55
(e/D = 2.0)	65	75	52	58	65
e, percent	3	5	5	3	3
E, 10^3 ksi	10.4				
E_c, 10^3 ksi	10.5				
G, 10^3 ksi	3.9				
μ	0.33				
Physical Properties:					
ω, lb/in.^{3}	0.097				
C, Btu/(lb)(F)	0.23 (at 212 F)				
K, Btu/[(hr)(ft^2)(F)/ft]	88 (at 77 F)				
α, 10^{-6} in./in./F	12.0 (68 to 212 F)				

[a] The attainable strength class number is dependent on the casting configuration, complexity, and size (both weight and wall thickness). Favorable experience with a particular configuration may allow some foundries to produce to a higher strength class number than others. In case of doubt regarding the strength class number, the designer should consult or negotiate with the foundry to determine the proper strength class number to assign for a specific casting.

[b] For any casting process; i.e., special mold, permanent mold, or sand mold (including chilling).

[c] The mechanical properties shown are reliably obtainable in castings of this alloy and heat-treat condition when produced under the quality assurance provisions of MIL-A-21180. These provisions require preproduction approval, documentation of foundry procedures, and specific destructive and nondestructive testing procedures for the acceptance of each production lot of castings. Strict adherence to these requirements is mandatory if these properties are to be reliably assured in each casting.

[d] Bearing values are "dry pin" values per Section 1.4.7.1.

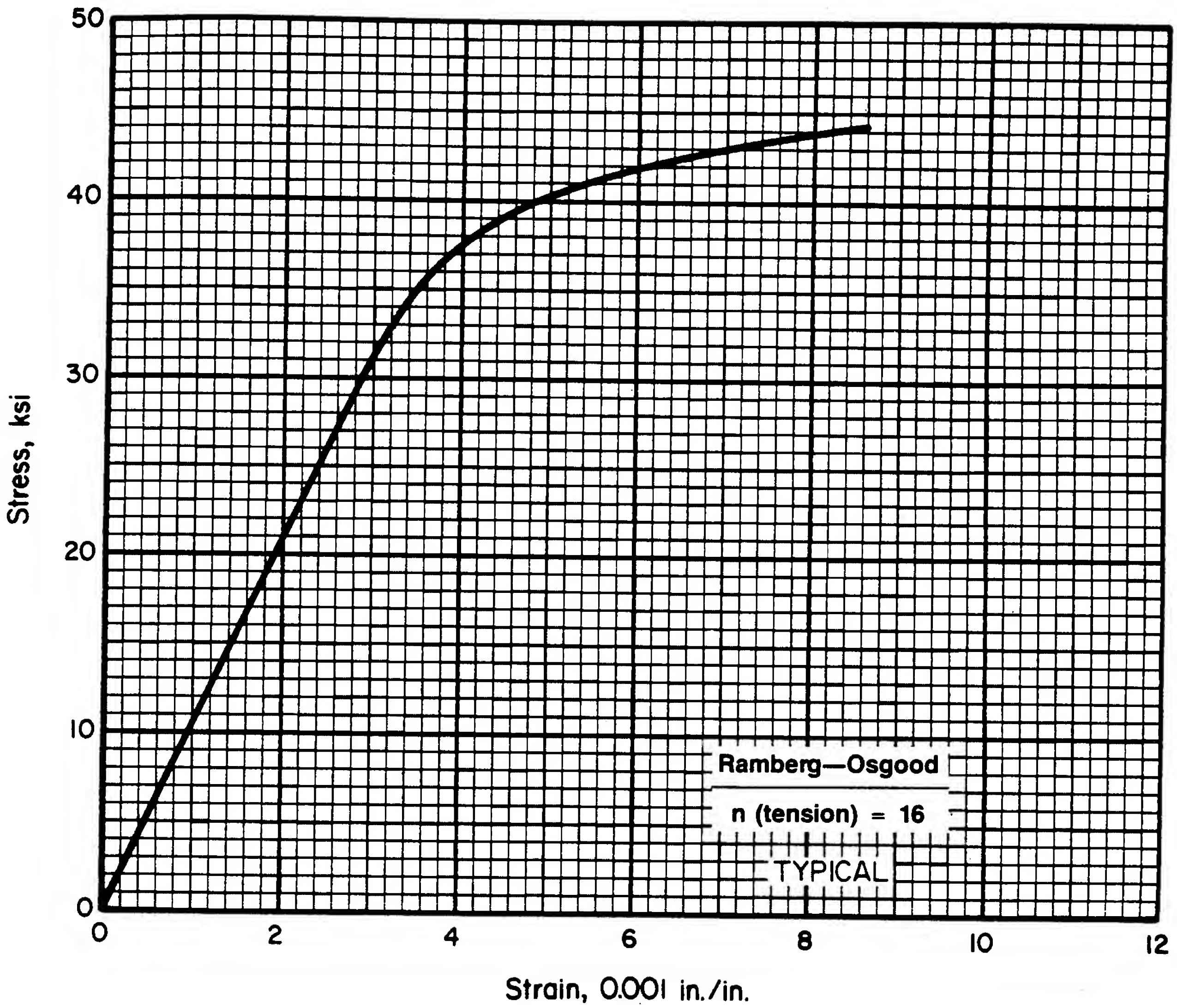

FIGURE 3.9.6.1.6. *Typical tensile stress-strain curve for A357.0-T6 aluminum alloy casting, Class 2, designated area, at room temperature.*

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3.9.7 D357.0 ALLOY

3.9.7.0 *Comments and Properties.*—D357.0 is a modification of A357.0 with narrower compositional limits and more stringent inspection requirements. These modifications were necessary to reduce variability in mechanical properties to a degree compatible with the determination of A and B values. D357.0 is a heat-treatable Al-Si-Mg alloy generally used for premium quality castings in which special properties are developed by careful control of casting and chilling techniques. It has excellent casting characteristics and provides high strength together with good toughness. The alloy also has excellent corrosion resistance. Refer to Section 3.1.3.4 for comments regarding the weldability of the alloy.

A material specification for D357.0 aluminum is presented in Table 3.9.7.0(a). Room temperature mechanical and physical properties are shown in Table 3.9.7.0(b).

TABLE 3.9.7.0(a). *Material Specification for D357.0 Aluminum Alloy*

Specification	Form
AMS 4241	Sand composite casting

The temper index for D357.0 is as follows:

Section	Temper
3.9.7.1	T6

3.9.7.1 *T6 Temper.*—Figure 3.9.7.1.6 presents a typical tensile stress-strain curve.

TABLE 3.9.7.0(b). *Design Mechanical and Physical Properties of D357.0 Aluminum Alloy Casting*

Specification	AMS 4241		
Form	Sand composite casting		
Temper	T6		
Thickness, in.	≤2.500		...
Location within casting	Designated area		Nondesignated area
Basis	A	B	S
Mechanical Properties[a]:			
F_{tu}, ksi	46	49	45
F_{ty}, ksi	39	41	36
F_{cy}, ksi	39	41	36
F_{su}, ksi	29	31	28
F_{bru}[b], ksi:			
(e/D = 1.5)	79	84	77
(e/D = 2.0)	99	105	96
F_{bry}[b], ksi:			
(e/D = 1.5)	62	65	57
(e/D = 2.0)	73	77	67
e, percent (S-basis)	3	...	2
E, 10^3 ksi	10.4		
E_c, 10^3 ksi	10.5		
G, 10^3 ksi	3.9		
μ	0.33		
Physical Properties:			
ω, lb/in.^{3}	0.097		
C, Btu/(lb)(F)	0.23 (at 212 F)		
K, Btu/[(hr)(ft^2)(F)/ft]	88 (at 77 F)		
α, 10^{-6} in./in./F	12.0 (68 to 212 F)		

[a] The mechanical properties shown are reliably obtainable when castings are produced under the quality assurance provisions of AMS 4241. These provisions require preproduction approval, documentation of foundry procedures, and specific destructive and nondestructive testing procedures for the acceptance of each production lot of castings. Strict adherence to these requirements is mandatory if these properties are to be reliably assured in each casting.

[b] Bearing values are "dry pin" values per Section 1.4.7.1.

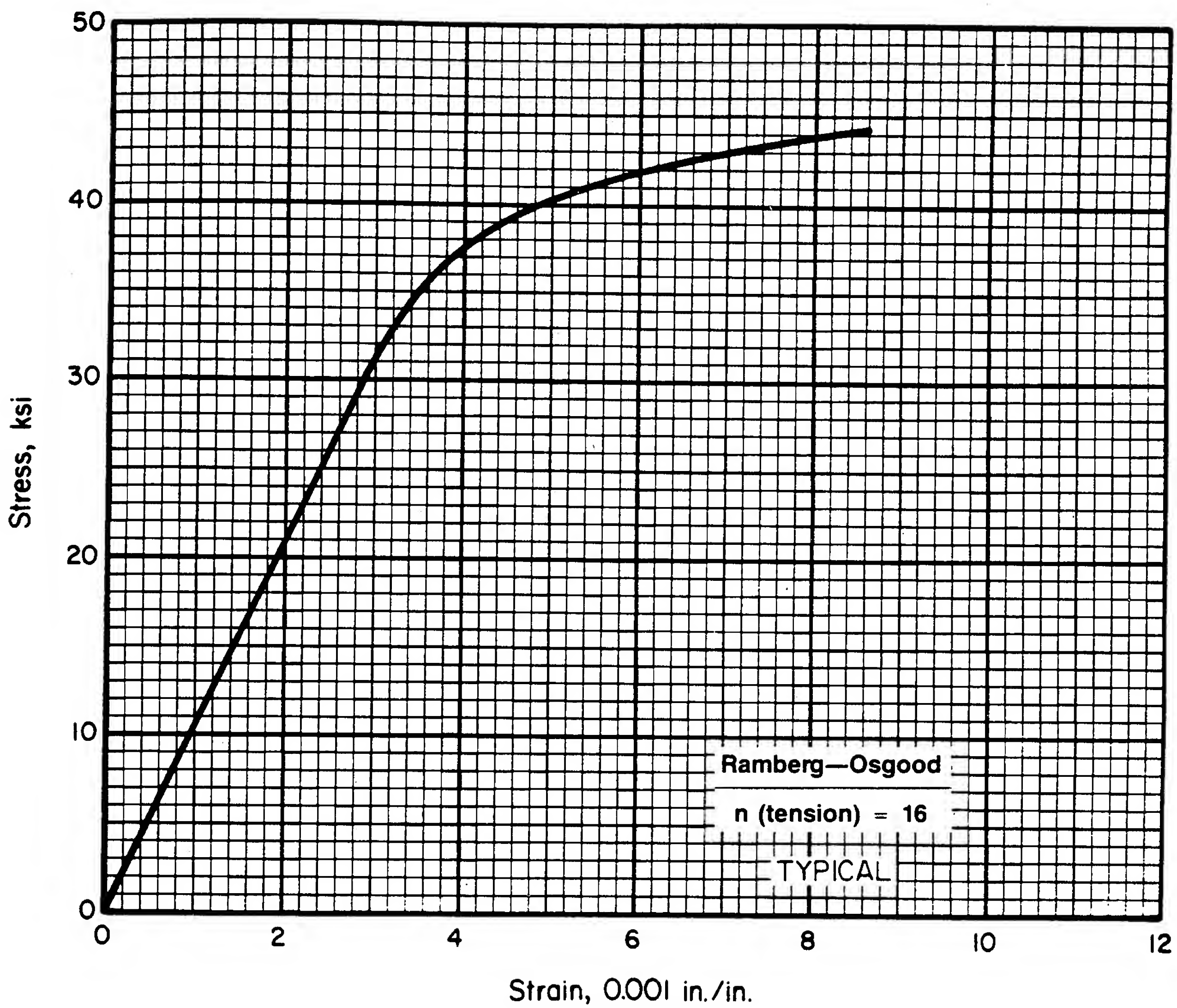

FIGURE 3.9.7.1.6. *Typical tensile stress-strain curve for D357.0-T6 aluminum alloy casting, designated area, at room temperature.*

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3.9.8 359.0 ALLOY

3.9.8.0 *Comments and Properties.*—359.0 is a relatively high-strength permanent-mold casting alloy. It is heat treatable, and has good corrosion resistance. Refer to Section 3.1.3.4 for comments regarding the weldability of the alloy.

A material specification for 359.0 aluminum alloy is presented in Table 3.9.8.0(a). Room-temperature mechanical and physical properties are shown in Table 3.9.8.0(b).

TABLE 3.9.8.0(a). *Material Specification for 359.0 Aluminum Alloy*

Specification	Form
MIL-A-21180	Casting

TABLE 3.9.8.0(b). *Design Mechanical and Physical Properties of 359.0 Aluminum Alloy Casting*

Specification	MIL-A-21180			
Form	Casting			
Temper	T6			
Location within casting	Designated area		Nondesignated area	
Strength class number[a]	1	2	10	11
Basis	S	S	S	S
Mechanical Properties[b,c]:				
F_{tu}, ksi:	45	47	45	40
F_{ty}, ksi:	35	38	34	30
F_{cy}, ksi:	35	38	34	30
F_{su}, ksi	28	29	28	25
F_{bru}, ksi:				
(e/D = 1.5)	77	81	77	69
(e/D = 2.0)	96	101	96	86
F_{bry}, ksi:				
(e/D = 1.5)	55	60	54	47
(e/D = 2.0)	65	71	63	56
e, percent	4	3	4	3
E, 10^3 ksi	10.5			
E_c, 10^3 ksi	10.7			
G, 10^3 ksi	4.0			
μ	0.33			
Physical Properties:				
ω, lb/in.^{3}	0.097			
C, Btu/(lb)(F)	0.23 (at 212 F)			
K, Btu/[(hr)(ft^2)(F)/ft]	88 (at 77 F)			
α, 10^{-6} in./in./F	11.0 (68 to 212 F)			

[a] The attainable strength class number is dependent on the casting configuration, complexity, and size (both weight and wall thickness). Favorable experience with a particular configuration may allow some foundries to produce to a higher strength class number than others. In case of doubt regarding the strength class number, the designer should consult or negotiate with the foundry to determine the proper strength class number to assign for a specific casting.

[b] For any casting process; i.e., special mold, permanent mold, or sand mold (including chilling).

[c] The mechanical properties shown are reliably obtainable in castings of this alloy and heat-treat condition when produced under the quality assurance provisions of MIL-A-21180. These provisions require preproduction approval, documentation of foundry procedures, and specific destructive and nondestructive testing procedures for the acceptance of each production lot of castings. Strict adherence to these requirements is mandatory if these properties are to be reliably assured in each casting.

3.11 Element Properties

3.11.1 BEAMS. See Equation 1.3.2.3, Section 1.5.2.5, and Reference 1.7.1 for general information on stress analysis of beams.

3.11.1.1 *Simple Beams.*—Beams of solid, tubular, or similar cross sections can be assumed to fail through exceeding an allowable modulus of rupture in bending (F_b). In the absence of specific data, the ratio F_b/F_{tu} can be assumed to be 1.25 for solid sections.

3.11.1.1.1 *Round Tubes.*—For round tubes, the value of F_b will depend on the D/t ratio as well as the ultimate tensile stress. The bending moduli of rupture of round tubes of various aluminum alloys are given in Figure 3.11.1.1.1. It should be noted that these values apply only when the tubes are restrained against local buckling at the loading points.

3.11.1.1.2 *Unconventional Cross Section.*—Sections other than solid or tubular should be tested to determine the allowable bending stress.

3.11.1.2 *Built-Up Beams.*—Built-up beams will usually fail because of local failures of the component parts. In aluminum-alloy construction, the strength of fittings and joints is an important feature (see Reference 3.11.1.2).

3.11.1.3 *Thin-Web Beams.*—The allowable stress for thin-web beams will depend on the nature of the failure and is determined from the allowable stresses of the web in tension and of the flanges or stiffeners in compression.

3.11.2 COLUMNS

3.11.2.1 *Primary Failure.*—The general formula for primary instability is given in Section 1.3.8.

3.11.2.2 *Local Failure.*—The local stability of aluminum alloy column sections may be determined using the methods outlined in References 3.11.2.2(a) through (e).

3.11.2.3 *Column Properties.*—Curves of the allowable column stresses for round and streamline tubing are given in Figure 3.11.2.3. The allowable stress is plotted against the effective slenderness ratio, defined by the formula:

$$\frac{L'}{\rho} = \frac{L}{\rho\sqrt{c}} \qquad (3.11.2.3)$$

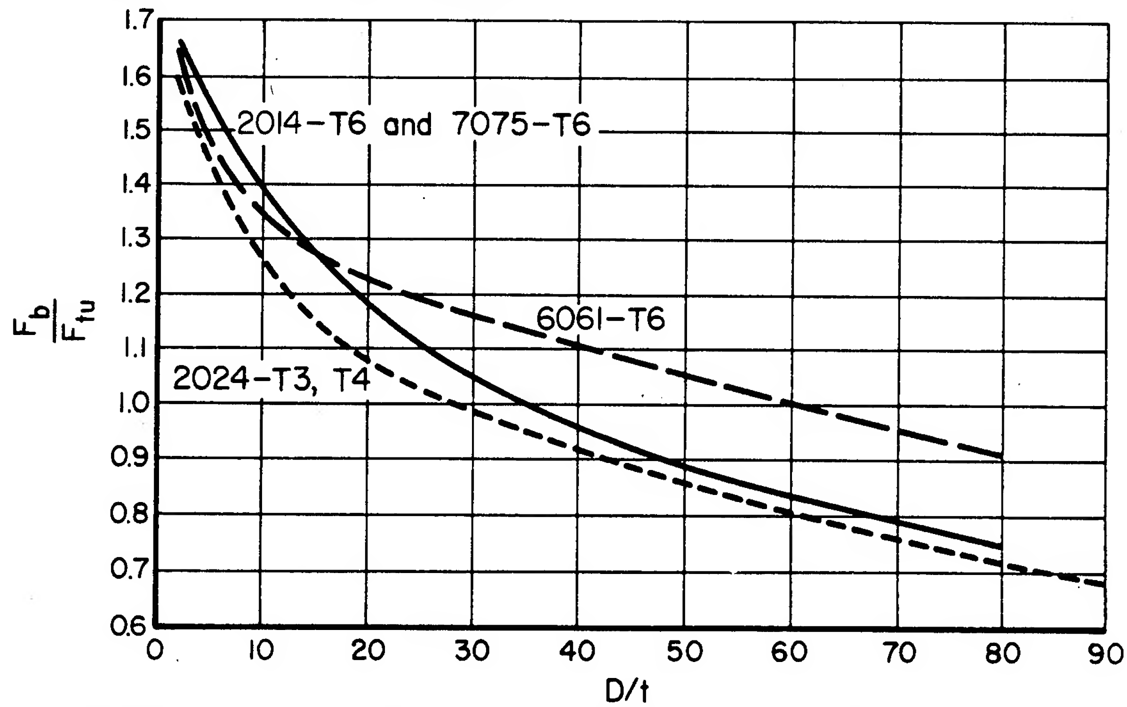
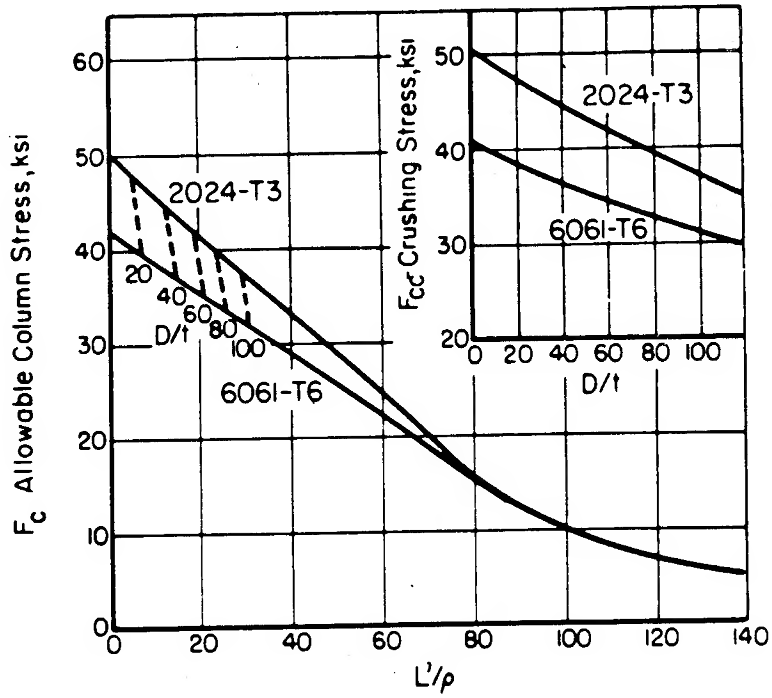
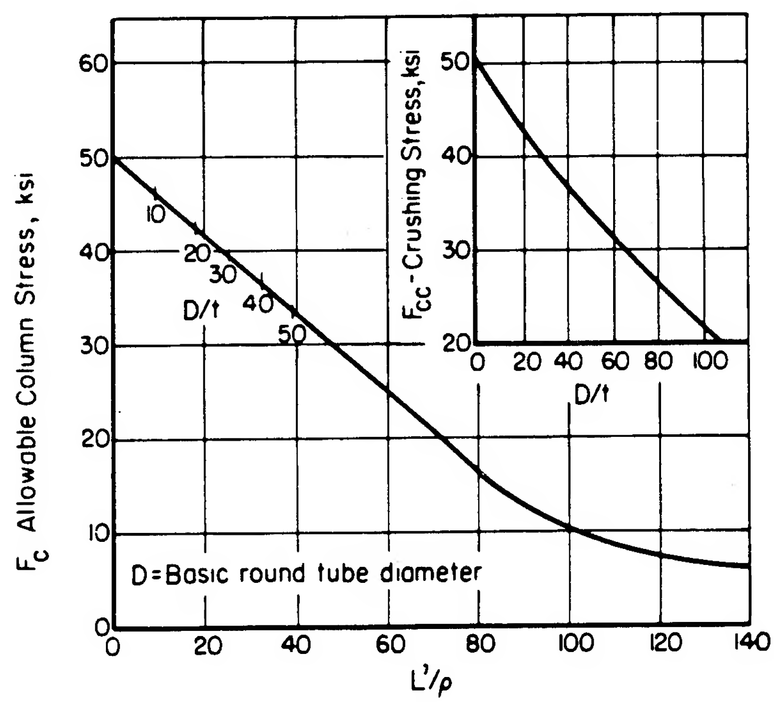


FIGURE 3.11.1.1.1. *Bending modulus of rupture for aluminum alloy round tubing.*



(a) Round 2024 and 6061 Tubing



(b) Streamline 2024–T3 Tubing

FIGURE 3.11.2.3. *Allowable column and crushing stresses for 2024 and 6061 aluminum alloy tubing.*

3.11.3 TORSION

3.11.3.1 *General*.--The torsional failure of aluminum-alloy tubes may be due to plastic failure of metal, elastic instability of the walls, or an intermediate condition. Pure shear failure will not usually occur within the range of wall thicknesses commonly used for aircraft tubing.

3.11.3.2 *Torsion Properties*.--The curves of Figures 3.11.3.2(a) through (g) are derived from the method outlined in reference 2.8.1.1 and take into account the parameter L/D. The theoretical results set forth in reference 2.8.3.2 have been found to be in good agreement with the experimental results.

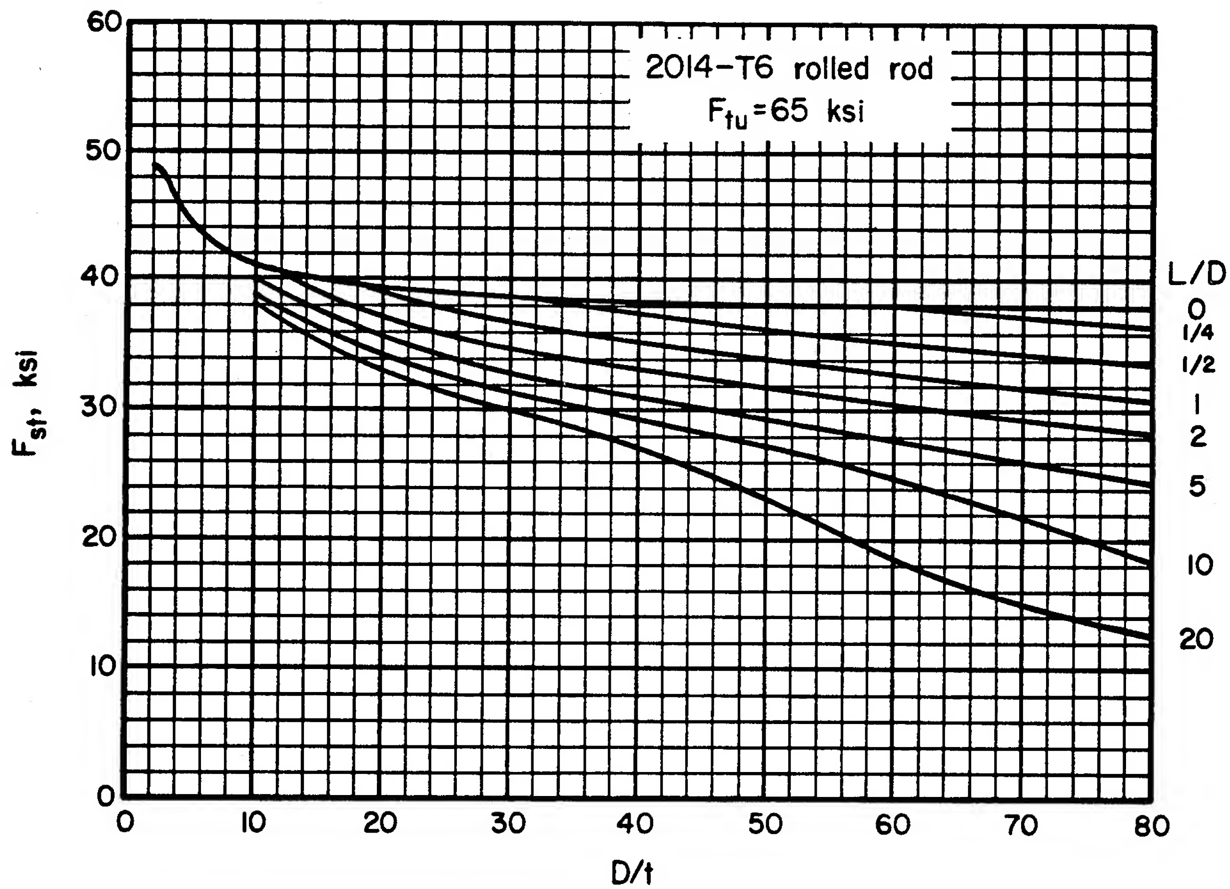


FIGURE 3.11.2.3.2(a). *Torsional modulus of rupture--2014-T6 aluminum alloy rolled rod.*

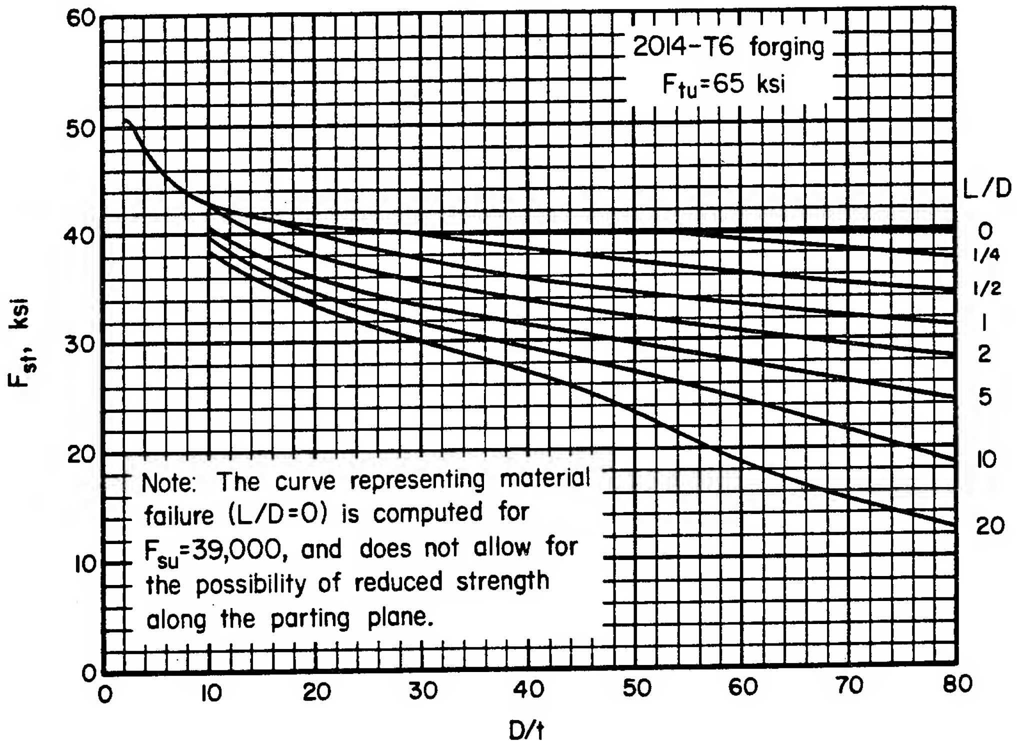


FIGURE 3.11.3.2(b). *Torsional modulus of rupture--2014-T6 aluminum alloy forging.*

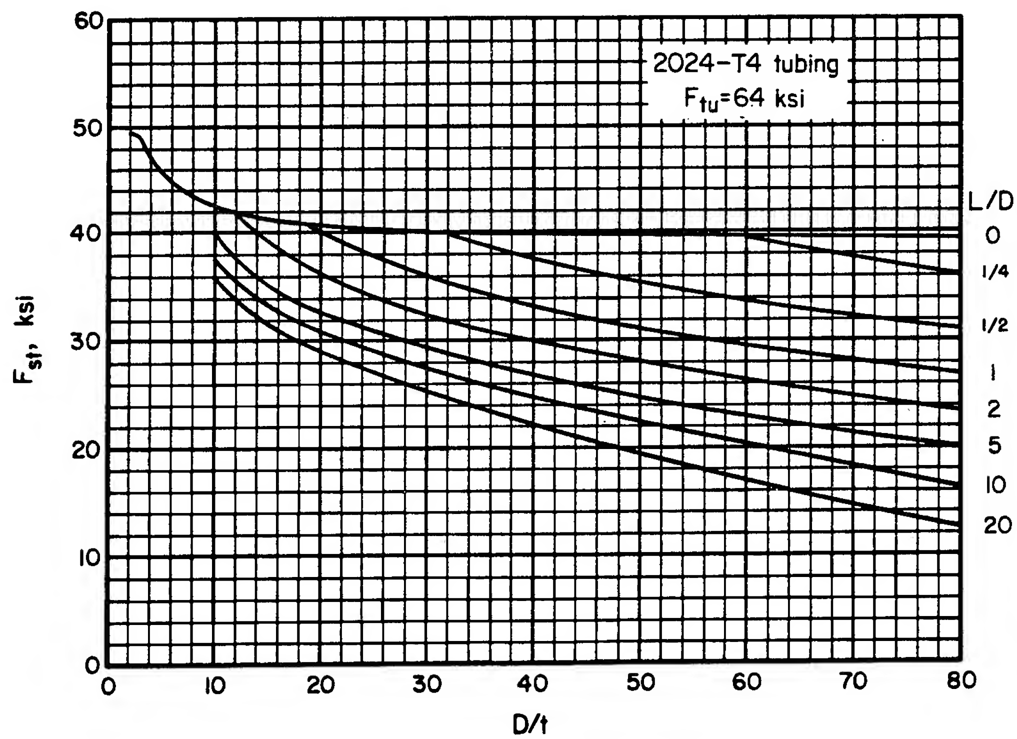


FIGURE 3.11.3.2(c). *Torsional modulus of rupture--2024-T3 aluminum alloy tubing.*

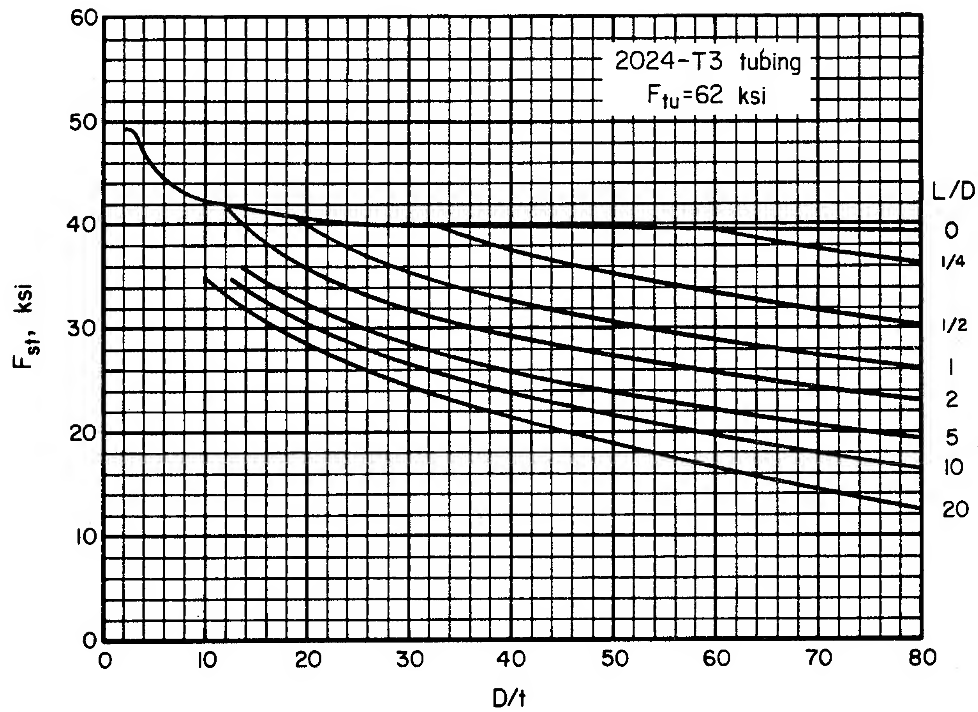


FIGURE 3.11.3.2(d). *Torsional modulus of rupture—2024-T4 aluminum alloy tubing.*

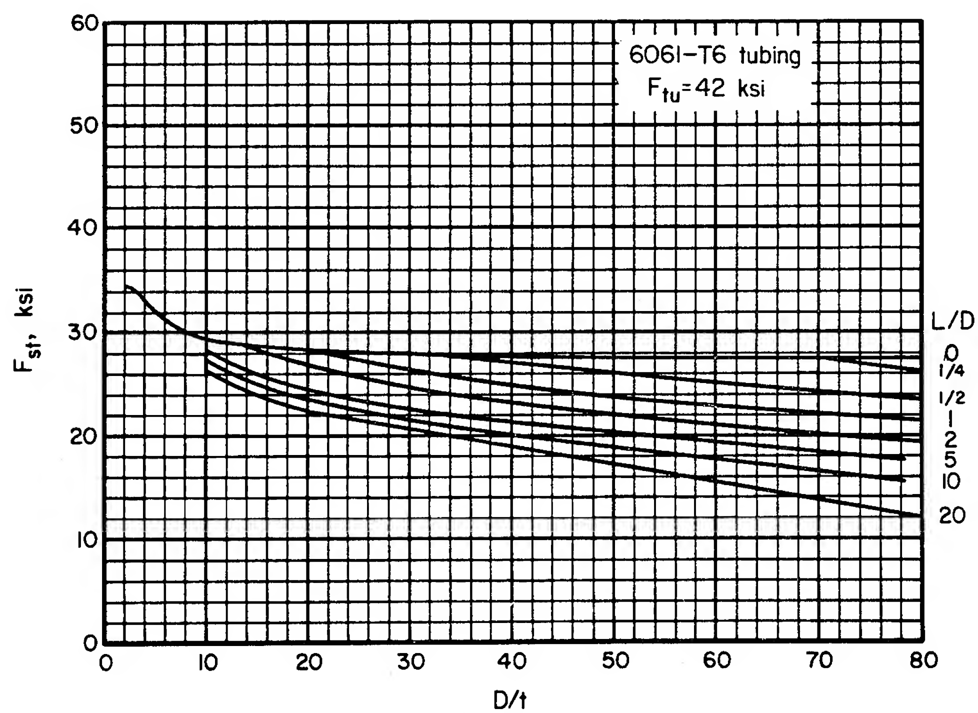


FIGURE 3.11.3.2(e). *Torsional modulus of rupture—6061-T6 aluminum alloy tubing.*

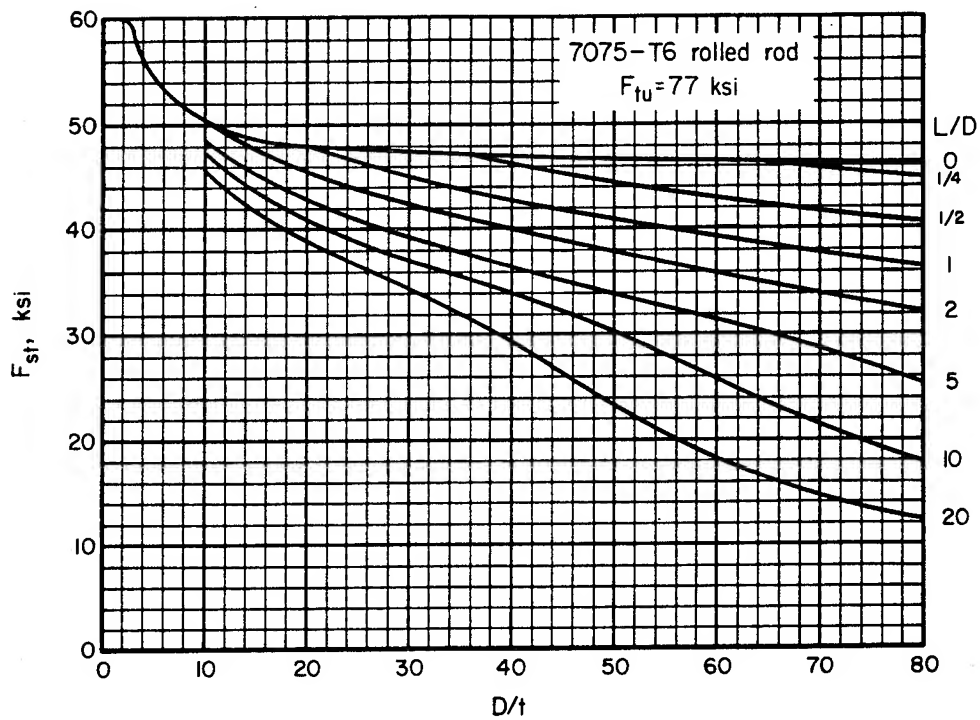


FIGURE 3.11.3.2(f). *Torsional modulus of rupture—7075-T6 aluminum alloy rolled rod.*

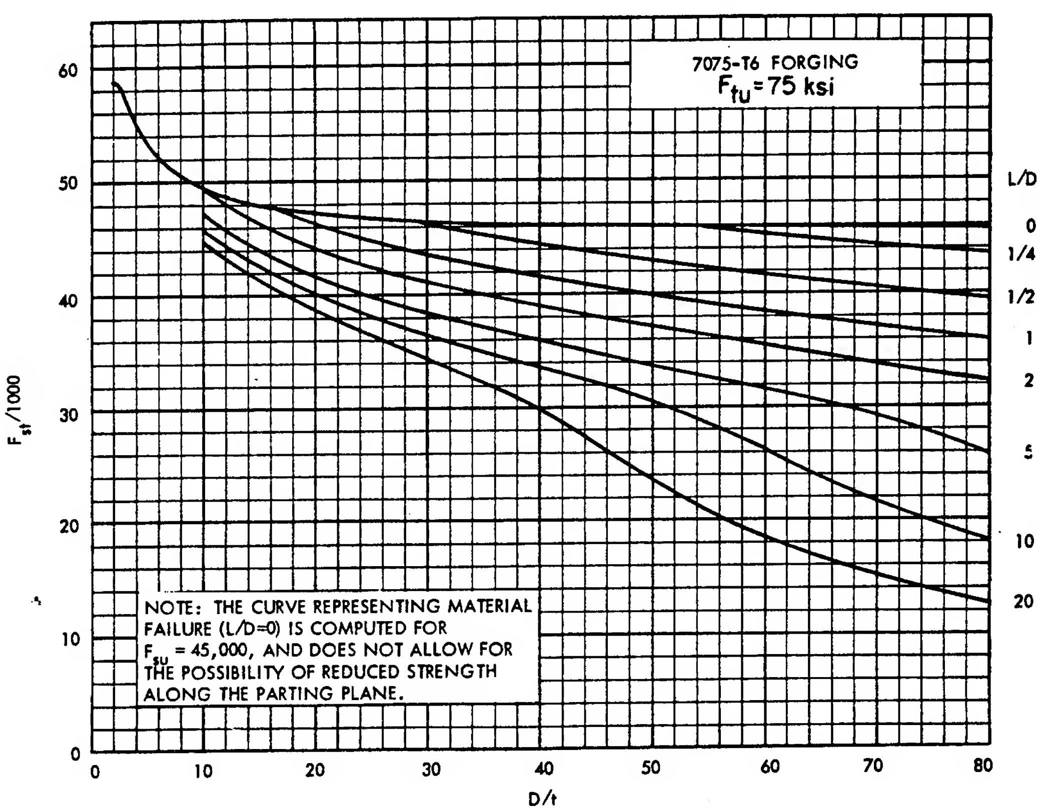


FIGURE 3.11.3.2(g). *Torsional modulus of rupture—7075-T6 aluminum alloy forging.*

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Chapter 4

MAGNESIUM ALLOYS

4.1 General

This chapter contains the engineering properties and characteristics of wrought and cast magnesium alloys used in aircraft and missile applications. Magnesium is a lightweight structural metal that can be strengthened greatly by alloying, and in some cases by heat treatment or cold work or by both.

4.1.1 ALLOY INDEX.—The magnesium alloys in this chapter are listed in alphanumeric sequence in each of two parts, the first one being wrought forms of magnesium and the second cast forms. These sections and the alloys covered under each are shown in Table 4.1.

TABLE 4.1. *Magnesium Alloys Index*

Section	Designation
4.2	**Magnesium-Wrought Alloys**
4.2.1	AZ31B
4.2.2	AZ61A
4.2.3	ZK60A
4.3	**Magnesium-Cast Alloys**
4.3.1	AM100A
4.3.2	AZ91C/AZ91E
4.3.3	AZ92A
4.3.4	EZ33A
4.3.5	QE22A
4.3.6	ZE41A

4.1.2 MATERIAL PROPERTIES

4.1.2.1 *Mechanical Properties.*—The mechanical properties are given either as design values or for information purposes. The tensile strength (F_{tu}), tensile yield strength (F_{ty}), elongation (e), and sometimes the compressive yield strength (F_{cy}) are guaranteed by procurement specifications. The properties obtained reflect the location of sample, type of test specimen and method of testing required by the product specification. The remaining design values are "derived" values; that is, sufficient tests have been made to ascertain that if a given material meets the requirements of the product specification, the material will have the compression (F_{cy}), shear (F_{su}) and bearing (F_{bru} and F_{bry}) strengths listed.

4.1.2.1.1 *Tension Testing.*—Room-temperature tension tests are made according to ASTM E 8. The yield strength (F_{ty}) is obtained by the "offset method" using an offset of 0.2 percent. The speed of testing for room-temperature tests has a small effect on the strength and elongation values obtained on most magnesium alloys. The rate of stressing generally specified to the yield strength is less than 100,000 psi per minute and the rate of straining from the yield strength to fracture is less than 0.5 in./in./min. It can be expected that the speed of testing used for room-temperature tension tests will approach the maximum permitted.

Elevated-temperature tension tests are made according to ASTM E 21. The speed of testing has a considerable effect on the results obtained and no one standard rate of straining is given in ASTM E 21. The strain rates most commonly used on magnesium are 0.005 in./in./min. to the yield and 0.10 in./in./min. from yield to fracture [see References 4.1.2.1.1(a) to (d)].

4.1.2.1.2 *Compression Testing.*—Compression test methods used for magnesium are specified in ASTM E 9. The values given for the compressive yield strength (F_{cy}), are taken at an offset of 0.2 percent. References 4.1.2.1.2(a) and (b) provide information on test techniques.

4.1.2.1.3 *Bearing Testing.*—Bearing tests of magnesium alloys are made according to ASTM E 238. The size of pin used has a significant effect on the values obtained, especially the bearing ultimate strength (F_{bru}). On tests made to obtain the data on magnesium alloys shown in this document, pin diameters of 0.187 and 0.250 inch were used. For pin diameters significantly larger than 0.250 inch lower values may be obtained. Additional information on bearing testing is given in References 4.1.2.1.3(a) and (b). Bearing values in the property tables are considered to be "dry pin" values in accordance with the discussion in Section 1.4.7.1.

4.1.2.1.4 *Shear Testing.*—The shear strength values used in this document were obtained by the "double shear" method using a pin-type specimen, the "punch shear" method and the "tension shear" method as applicable. Just as tensile ultimate strength (F_{tu}) values vary with location and direction of sample in relation to the method of fabrication, the shear strength (F_{su}) may be expected to reflect the effect of orientation, either as a function of the sampling or the maximum stresses imposed by the method of test. Information on shear testing is given in Reference 4.1.2.1.4.

4.1.2.1.5 *Shear Raisers.*—The effect of notches, holes, and stress raisers on the static properties of magnesium alloys is described in References 4.1.2.1.5(a) through (c). Additional data on the strength proprties of magnesium alloys are presented in References 4.1.2.1.5(d) through (h).

4.1.2.1.6 *Creep.*—Some creep data on magnesium alloys are summarized in Reference 4.1.2.1.6.

4.1.2.1.7 *Fatigue.*—Room-temperature axial load fatigue data for several magnesium alloys are presented in appropriate alloy sections. References 4.1.2.1.7(a) and (b) provide additional data on fatigue of magnesium alloys.

4.1.3 PHYSICAL PROPERTIES.—Selected experimental data from the literature were used in determining values for physical properties. In other cases, enough information was available to calculate the constants. Estimated values of some of the remaining constants were also included. Estimated values are noted.

4.1.4 ENVIRONMENTAL CONSIDERATIONS.—Corrosion protection must be considered for all magnesium applications. Protection can be provided by anodic films, chemical conversion coatings, paint systems, platings, or a combination of these methods. Proper drainage must be provided to prevent entrapment of water or other fluids. Dissimilar metal joints must be properly and completely insulated, including barrier strips and sealants.

Strain-hardened or age-hardened alloys may be annealed or overaged by prolonged exposure to elevated temperatures, with a resulting decrease in strength. Maximum recommended temperatures for prolonged service are reported, where available, for specific alloys.

4.1.5 ALLOY AND TEMPER DESIGNATIONS.—Standard ASTM nomenclature is used for the alloys listed. Temper designations are given in ASTM B 296. A summary of the temper designations is given in Table 4.1.5.

4.1.6 JOINING METHODS.—Most magnesium alloys may be welded; refer to "Comments and Properties" in individual alloy sections. Adhesive bonding and brazing may be used to join magnesium to itself or other alloys. All types of mechanical fasteners may be used to join magnesium. Refer to Section 4.1.4 when using mechanical fasteners or joining of dissimilar materials with magnesium alloys.

TABLE 4.1.5. *Temper Designation System for Magnesium Alloys*

Temper Designation System[a]

This temper designation system is used for all forms of wrought and cast magnesium and magnesium alloy products except ingots. It is based on the sequence of basic treatments used to produce the various tempers. The temper designation follows the alloy designation, the two being separated by a hyphen. Basic temper designations consist of letters. Subdivisions of the basic tempers, where required, are indicated by one or more digits following the letter. These designate specific sequences of basic treatments, but only operations recognized as significantly influencing the characteristics of the product are indicated. Should some other variation of the same sequence of basic operations be applied to the same alloy, resulting in different characteristics, then additional digits are added to the designation.

NOTE—In material specifications containing reference to two or more tempers of the same alloy which result in identical mechanical properties, the distinction between the tempers should be covered in suitable explanatory notes.

Basic Temper Designations

F — **as fabricated.** Applies to the products of shaping processes in which no special control over thermal conditions or strain-hardening is employed.

O — **annealed recrystallized (wrought products only).** Applies to wrought products which are annealed to obtain the lowest strength temper.

H — **strain-hardened (wrought products only).** Applies to products which have their strength increased by strain-hardening, with or without supplementary thermal treatments to produce some reduction in strength. The H is always followed by two or more digits.

W — **solution heat-treated.** An unstable temper applicable only to alloys which spontaneously age at room temperature after solution heat-treatment. This designation is specific only when the period of natural aging is indicated: for example, W ½ hr.

T — **thermally treated to product stable tempers other than F, O, or H.** Applies to products which are thermally treated, with or without supplementary strain-hardening, to product stable tempers. The T is always followed by one or more digits.

Subdivisions of H Temper: Strain-Hardened

The first digit following H indicates the specific combination of basic operations, as follows:

H1 — **strain-hardened only.** Applies to products which are strain-hardened to obtain the desired strength without supplementary thermal treatment. The number following this designation indicates the degree of strain-hardening.

H2 — **strain-hardened and partially annealed.** Applies to products which are strain-hardened more than the desired final amount and then reduced in strength to the desired level by partial annealing. The number following this designation indicates the degree of strain-hardening remaining after the product has been partially annealed.

H3 — **strain-hardened and stabilized.** Applies to products which are strain-hardened and whose mechanical properties are stabilized by a low temperature thermal treatment to

[a]From ASTM B 296.

TABLE 4.1.5. *Temper Designation System for Magnesium Alloys—Continued*

slightly lower strength and increase ductility. The number following this designation indicates the degree of strain-hardening remaining after the stabilization treatment.

The digit following the designations H1, H2, and H3 indicates the final degree of strain hardening. Tempers between 0 (annealed) and 8 (full-hard) are designated by numerals 1 through 7. Material having an ultimate tensile strength about midway between that of the 0 temper and that of the 8 temper is designated by the numeral 4; about midway between the 0 and 4 tempers by the numeral 2; and about midway between 4 and 8 tempers by the numeral 6, etc. Numeral 9 designates tempers whose minimum ultimate tensile strength exceeds that of the 8 temper.

The third digit, when used, indicates a variation of a two-digit temper. It is used when the degree of control of temper or the mechanical properties or both differ from, but are close to, that (or those) for the two-digit H temper designation to which it is added. Numerals 1 through 9 may be arbitrarily assigned as the third digit for an alloy and product to indicate a specific degree of control of temper or special mechanical property limits.

Subdivisions of T Temper: Thermally Treated

Numerals 1 through 10 following the T indicate specific sequences of basic treatments, as follows.

T1 **cooled from an elevated temperature shaping process and naturally aged to a substantially stable condition.** Applies to products for which the rate of cooling from an elevated temperature shaping process, such as casting or extrusion, is such that their strength is increased by room temperature aging.

T2 **annealed (castings only).** Applies to a type of annealing treatment used to improve ductility and increase stability.

T3 **solution heat-treated and cold worked.** Applies to products which are cold worked to improve strength after solution heat-treatment, or in which the effect of cold work in flattening or straightening is recognized in mechanical property limits.

T4 **solution heat-treated and naturally aged to a substantially stable condition.** Applies to products which are not cold worked after solution heat-treatment, or in which the effect of cold work in flattening or straightening may not be recognized in mechanical property limits.

T5 **cooled from an elevated temperature shaping process and artificially aged.** Applies to products which are cooled from an elevated temperature shaping process, such as casting or extrusion, and artificially aged to improve mechanical properties or dimensional stability or both.

T6 **solution heat-treated and artificially aged.** Applies to products which are not cold worked after solution heat-treatment, or in which the effect of cold work in flattening or straightening may not be recognized in mechanical property limits.

T7 **solution heat-treated and stabilized.** Applies to products that are stabilized after solution heat-treatment to carry them beyond a point of maximum strength to provide control of some special characteristic.

T8 **solution heat-treated, cold worked, and artificially aged.** Applies to products which are cold worked to improve strength, or in which the effect of cold work in flattening or straightening is recognized in mechanical property limits.

T9 **solution heat-treated, artificially aged, and cold worked.** Applies to products which are cold worked to improve strength.

TABLE 4.1.5. *Temper Designation System for Magnesium Alloys—Continued*

T10	**cooled from an elevated temperature shaping process, artificially aged, and cold worked.** Applies to products which are artificially aged after cooling from an elevated temperature shaping process, such as extrusion, and cold worked to further improve strength.

Additional digits, the first of which shall not be zero, may be added to designations T1 through T10 to indicate a variation in treatment which significantly alters the product characteristics[b] that are or would be obtained using the basic treatment.

[b]For this purpose, characteristic is something other than mechanical properties.

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4.2 Magnesium-Wrought Alloys

4.2.1 AZ31B

4.2.1.0 *Comments and Properties.*—AZ31B is a wrought magnesium-base alloy containing aluminum and zinc. It is available in the form of sheet, plate, extruded sections, forgings, and tubes. AZ31B has good room-temperature strength and ductility and is used primarily for applications where the temperature does not exceed 300 F. Increased strength is obtained in the sheet and plate form by strain hardening with a subsequent partial anneal (H24 and H26 temper). No treatments are available for increasing the strength of this alloy after fabrication.

Forming of AZ31B must be done at elevated temperatures if small radii or deep draws are required. If the temperatures used are too high or the times too great, H24 and H26 temper material will be softened. This alloy is readily welded but must be stress relieved after welding to prevent stress corrosion cracking.

Material specifications covering AZ31B wrought products are given in Table 4.2.1.0(a). Room-temperature mechanical and physical properties are shown in Tables 4.2.1.0(b) through (d). The effect of temperature on physical properties is shown in Figure 4.2.1.0.

TABLE 4.2.1.0(a). *Material Specifications for AZ31B Magnesium Alloy*

Specification	Form
AMS 4375	Sheet and plate
AMS 4376	Plate
AMS 4377	Sheet and plate
ASTM B107	Extrusion
QQ-M-40	Forging

The temper index for AZ31B is as follows:

Section	Temper
4.2.1.1	O
4.2.1.2	H24
4.2.1.3	H26
4.2.1.4	F

4.2.1.1 *AZ31B-O Temper.*—Effect of temperature on the tensile modulus of sheet and plate is presented in Figure 4.2.1.1.4. Typical room-temperature stress-strain and tangent-modulus curves are presented in Figure 4.2.1.1.6.

4.2.1.2 *AZ31B-H24 Temper.*—Effect of temperature on the mechanical properties of sheet and plate is shown in Figures 4.2.1.2.1 through 4.2.1.2.4, and 4.2.1.2.6. Typical room-temperature tension and compression stress-strain and tangent-modulus curves for sheet are shown in Figure 4.2.1.2.6.

4.2.1.3 *AZ31B-H26 Temper.*

4.2.1.4 *AZ31B-F Temper.*—Figures 4.2.1.4.8 (a) and (b) contain fatigue data for forged disk at room temperature.

TABLE 4.2.1.0(b). *Design Mechanical and Physical Properties of AZ31B Magnesium Alloy Sheet and Plate*

Specification	AMS 4375					AMS 4377						
Form	Sheet		Plate			Sheet		Plate				
Temper	0					H24						
Thickness, in.	0.016-0.060	0.061-0.249	0.250-0.500	0.501-2.000	2.001-3.000	0.016-0.062	0.063-0.249	0.250-0.374	0.375-0.500	0.501-1.000	1.001-2.000	2.001-3.000
Basis	S	S	S	S	S	S	S	S	S	S	S	S
Mechanical Properties:												
F_{tu}, ksi:												
L	32	32	32	32	32	39	39	38	37	36	34	34
LT	...	...	...	...	...	40	40	39	38	37	35	...
F_{ty}, ksi:												
L	18	15	15	15	15	29	29	26	24	22	20	18
LT	...	...	...	...	...	32	32	29	27	25	23	...
F_{cy}, ksi:												
L	...	12	10	10	8	...	24	20	16	13	10	9
LT[a]	...	...	...	...	...	...	...	...	...	...	...	...
F_{su}, ksi	17	17	17	...	...	18	18	18	18	...	...	...
F_{bru}[b], ksi:												
(e/D = 1.5)	50	50	50	...	...	58	58	56	54	...	...	...
(e/D = 2.0)	60	60	60	...	...	68	68	65	63	...	...	...
F_{bry}[b], ksi:												
(e/D = 1.5)	29	29	27	...	...	43	43	38	34	...	...	...
(e/D = 2.0)	29	29	27	...	...	43	43	38	34	...	...	...
e, percent												
L	12	12	12	10	9	6	6	8	8	8	8	8
E, 10^3 ksi	6.5											
E_c, 10^3, ksi	6.5											
G, 10^3, ksi	2.4											
μ	0.35											
Physical Properties:												
ω, lb/in.^{3}	0.0639											
C, K, and α	See Figure 4.2.1.0											

[a] F_{cy}(LT) allowables are equal to or greater than F_{cy}(L) allowables.
[b] Bearing values are "dry pin" values per Section 1.4.7.1.

TABLE 4.2.1.0(c). *Design Mechanical and Physical Properties of AZ31B Magnesium Alloy Plate*

Specification	ASTM B 107						
Form	Plate						
Temper	H26						
Thickness[a], in.	0.250-0.375	0.376-0.438	0.439-0.500	0.501-0.750	0.751-1.000	1.001-1.500	1.501-2.000
Basis	S	S	S	S	S	S	S
Mechanical Properties:							
F_{tu}, ksi:							
L	39	38	38	37	37	35	35
LT	40	39	39	38	38	36	36
F_{ty}, ksi:							
L	27	26	26	25	23	22	21
LT	30	29	29	28	26	25	24
F_{cy}, ksi:							
L	22	21	18	17	16	15	14
LT[a]	...	...	....	...	...	...	...
F_{su}, ksi	18	18	18	...	...	...	...
F_{bru}[b], ksi:							
(e/D = 1.5)	58	56	56	...	...	...	...
(e/D = 2.0)	68	65	65	...	...	...	...
F_{bry}[b], ksi:							
(e/D = 1.5)	40	39	36	...	...	...	...
(e/D = 2.0)	40	39	36	...	...	...	...
e, percent:							
L	6	6	6	6	6	6	6
E, 10^3 ksi	6.5						
E_c, 10^3, ksi	6.5						
G, 10^3, ksi	2.4						
μ	0.35						
Physical Properties:							
ω, lb/in.^{3}	0.0639						
C, K, and α	See Figure 4.2.1.0						

[a] F_{cy}(LT) allowables are equal to or greater than F_{cy}(L) values.
[b] Bearing values are "dry pin" values per Section 1.4.7.1.

TABLE 4.2.1.0(d). *Design Mechanical and Physical Properties of AZ31B Magnesium Alloy Extrusion and Forging*

Specification	ASTM B 107							QQ-M-40
Form	Erxtruded bar, rod, and solid shapes				Extruded hollow shapes	Extruded tube		Forging
Temper	F							
Thickness[a], in.	≤0.249	0.250-1.499	1.500-2.499	2.500-4.999	All	0.028-0.250[b]	0.251-0.750[b]	...
Basis	S	S	S	S	S	S	S	S
Mechanical Properties:								
F_{tu}, ksi:								
L	35	35	34	32	32	32	32	34
LT	...	...	...	...	...	...	...	...
F_{ty}, ksi:								
L	21	22	22	20	16	16	16	19
LT	...	...	...	...	...	...	...	...
F_{cy}, ksi:								
L	...	12	12	10	10	10	10	...
LT	...	...	...	...	...	...	...	...
F_{su}, ksi	17	17	17	...	...	...	...	...
$F_{bru}{}^{c}$, ksi:								
(e/D = 1.5)	36	36	36	...	...	...	...	...
(e/D = 2.0)	45	45	45	...	...	...	...	...
$F_{bry}{}^{c}$, ksi:								
(e/D = 1.5)	23	23	23	...	...	...	...	...
(e/D = 2.0)	23	23	23	...	...	...	...	...
e, percent:								
L	7	7	7	7	8	8	4	6
E, 10^3 ksi	6.5							
E_c, 10^3, ksi	6.5							
G, 10^3, ksi	2.4							
μ	0.35							
Physical Properties:								
ω, lb/in.^{3}	0.0639							
C, K, and α	See Figure 4.2.1.0							

[a]Wall thickness for tube.
[b]For outside diameter ≤6.000 inches.
[c]Bearing values are "dry pin" values per Section 1.4.7.1.

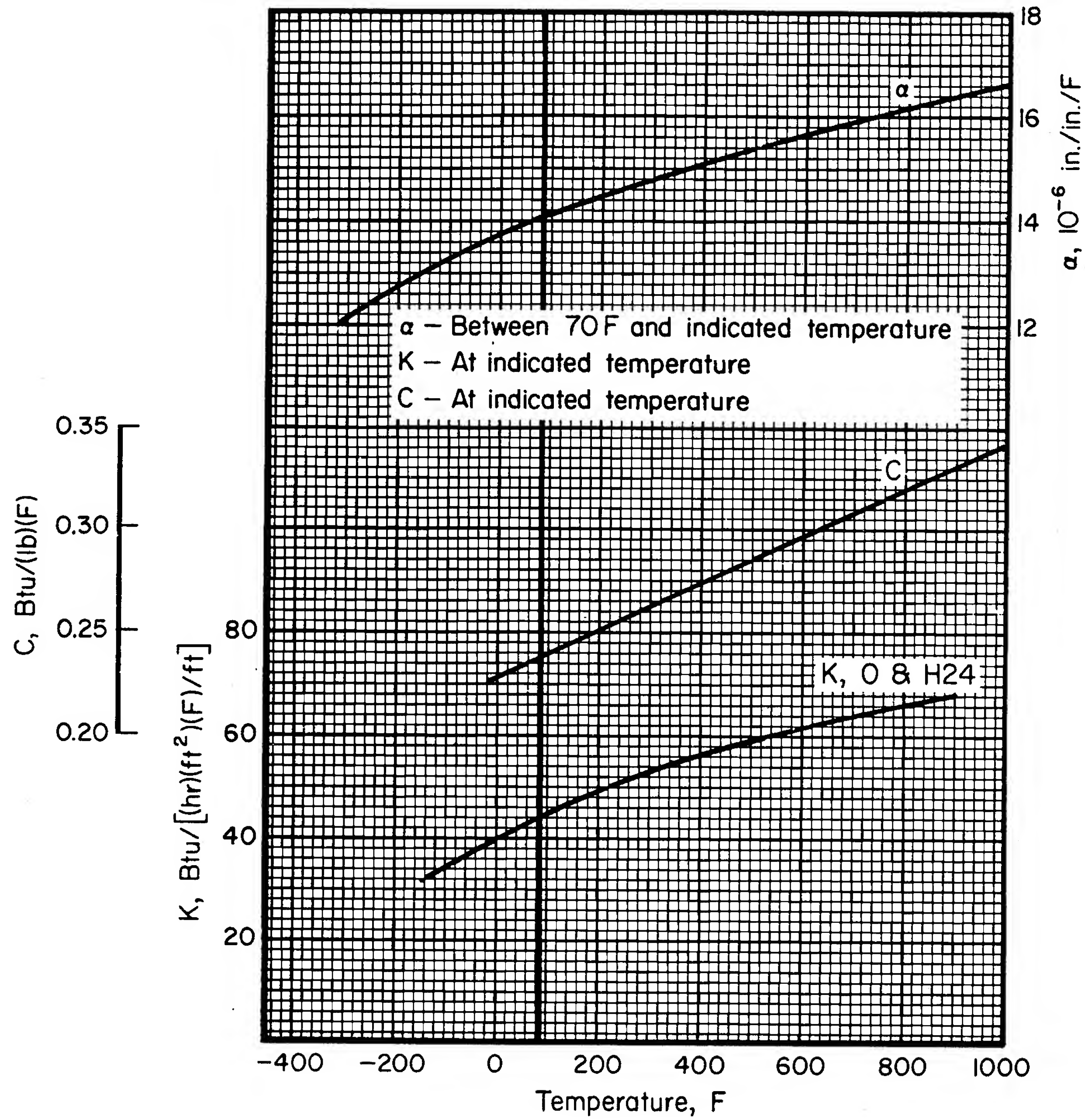

FIGURE 4.2.1.0. *Effect of temperature on the physical properties of AZ31B.*

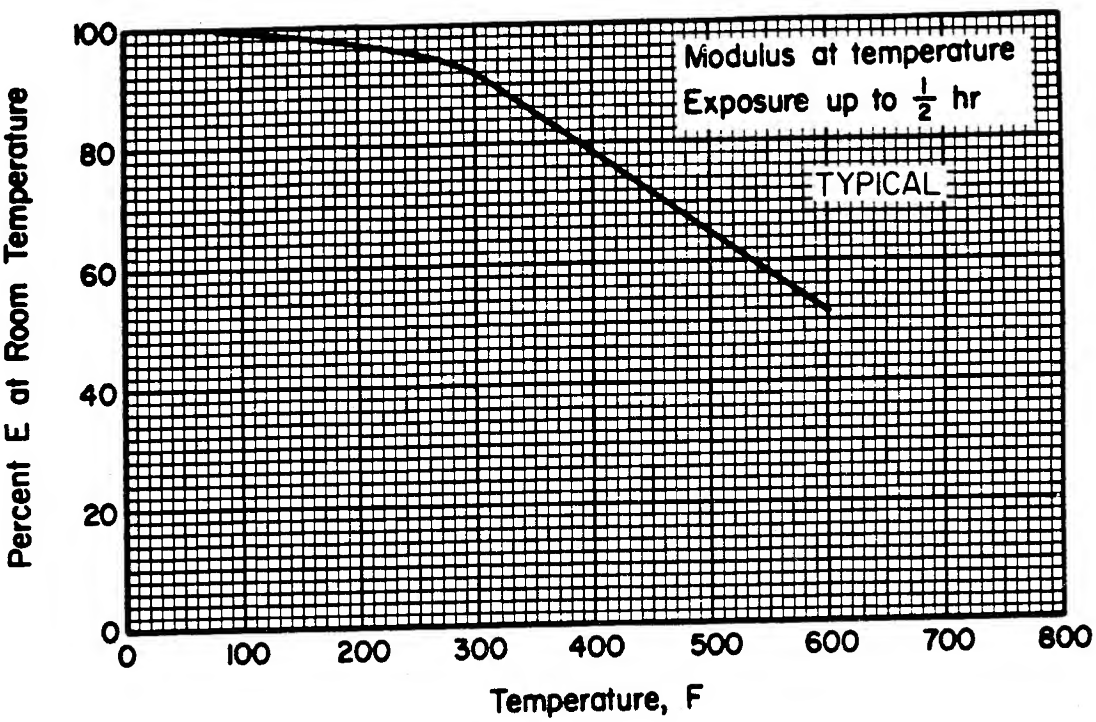

FIGURE 4.2.1.1.4. *Effect of temperature on the tensile modulus (E) of AZ31B-O sheet and plate.*

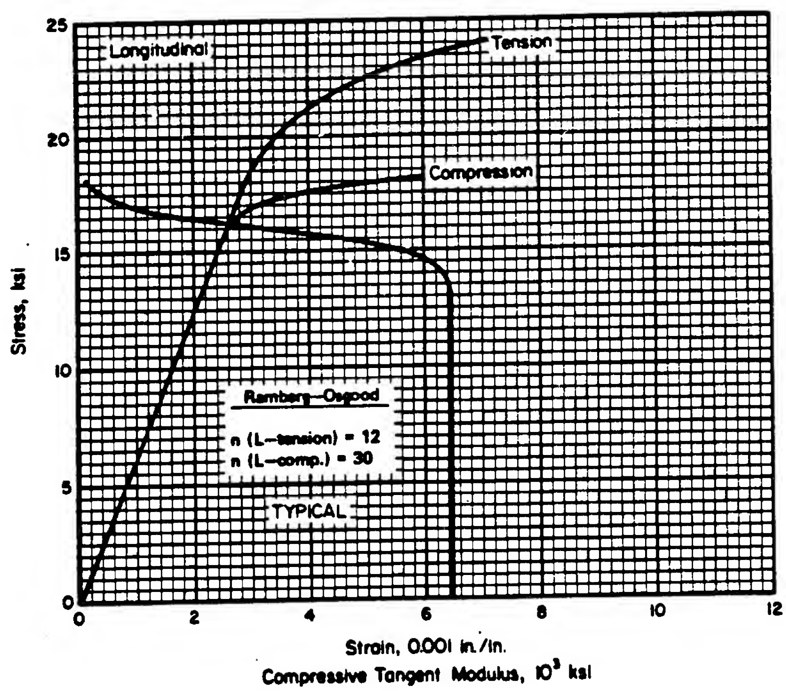

FIGURE 4.2.1.1.6. *Typical tensile and compressive stress-strain and compressive tangent-modulus curves for AZ31B-O sheet and plate at room temperature.*

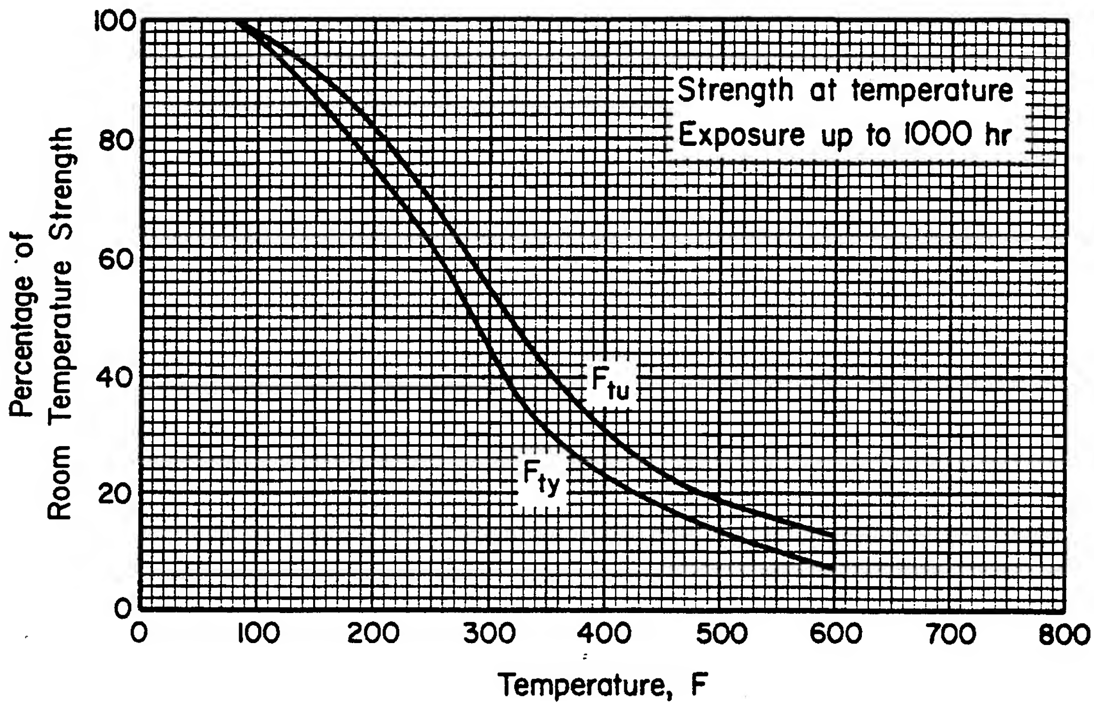

FIGURE 4.2.1.2.1. *Effect of temperature on the tensile ultimate strength (F_{tu}) and the tensile yield strength (F_{ty}) of AZ31B-H24 sheet and plate.*

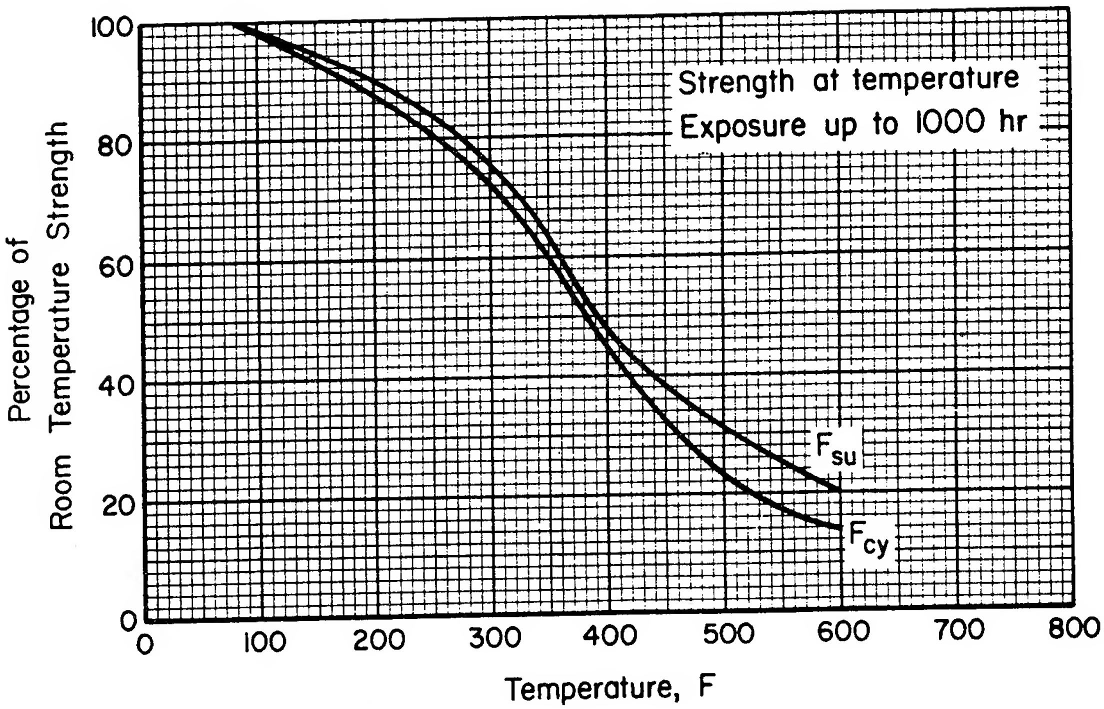

FIGURE 4.2.1.2.2. *Effect of temperature on the compressive yield strength (F_{cy}) and the shear ultimate strength (F_{su}) of AZ31B-H24 sheet and plate.*

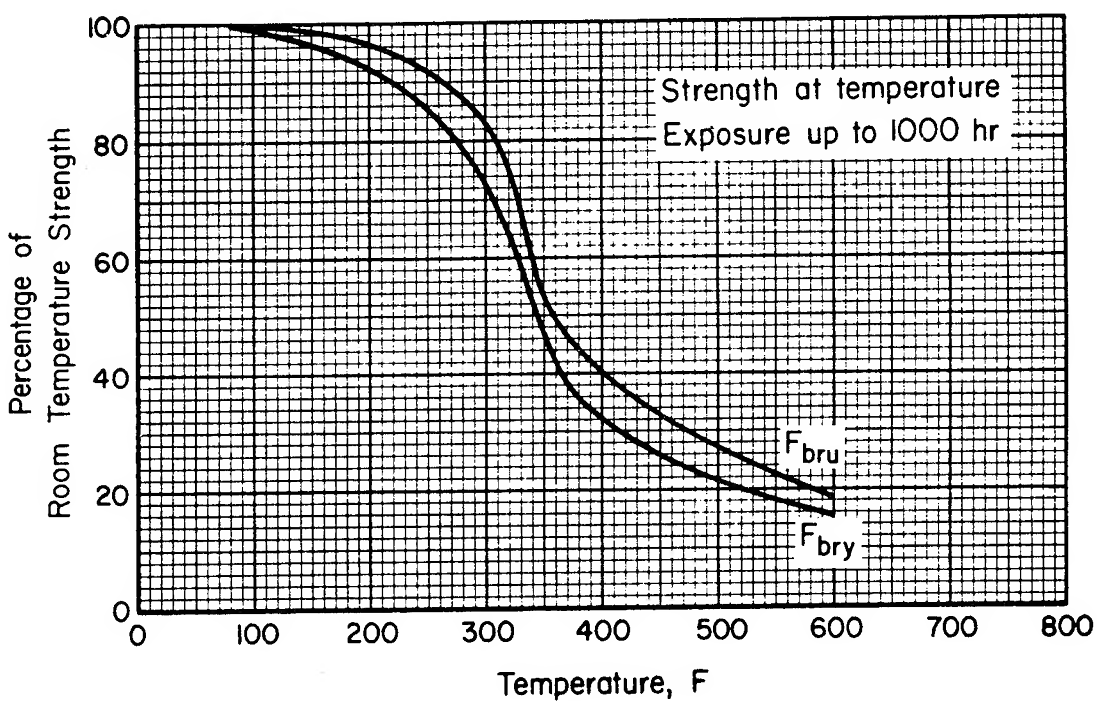

FIGURE 4.2.1.2.3. *Effect of temperature on the bearing ultimate strength (F_{bru}) and the bearing yield strength (F_{bry}) of AZ31B-H24 sheet and plate.*

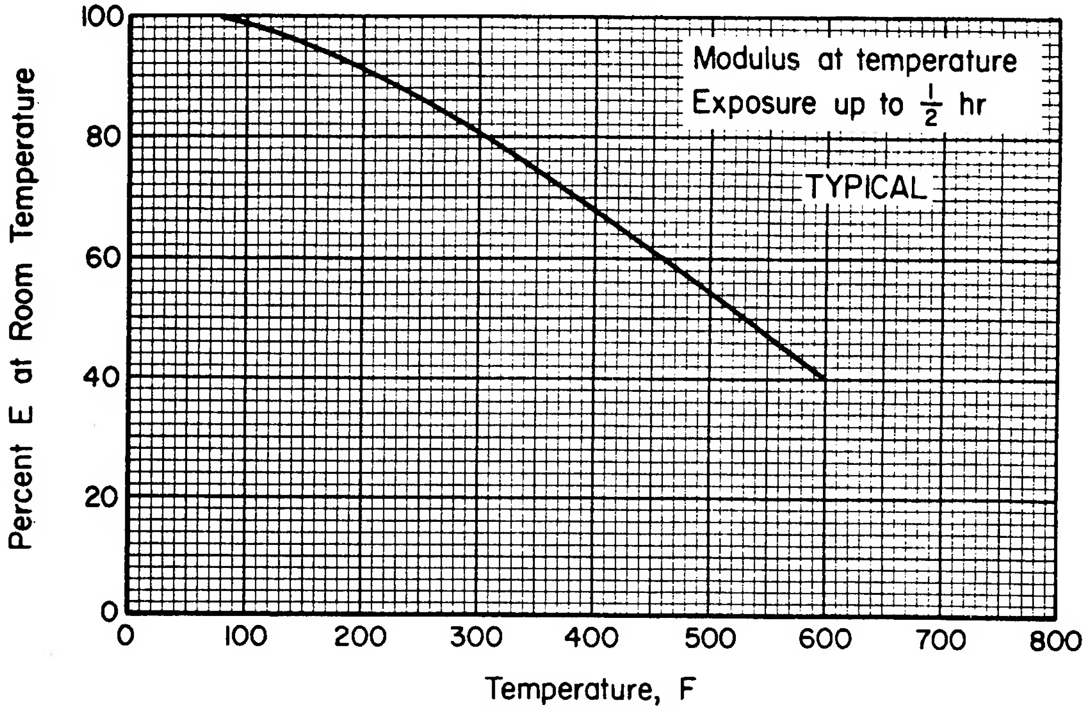

FIGURE 4.2.1.2.4. *Effect of temperature on the tensile modulus (E) of AZ31B-H24 sheet and plate.*

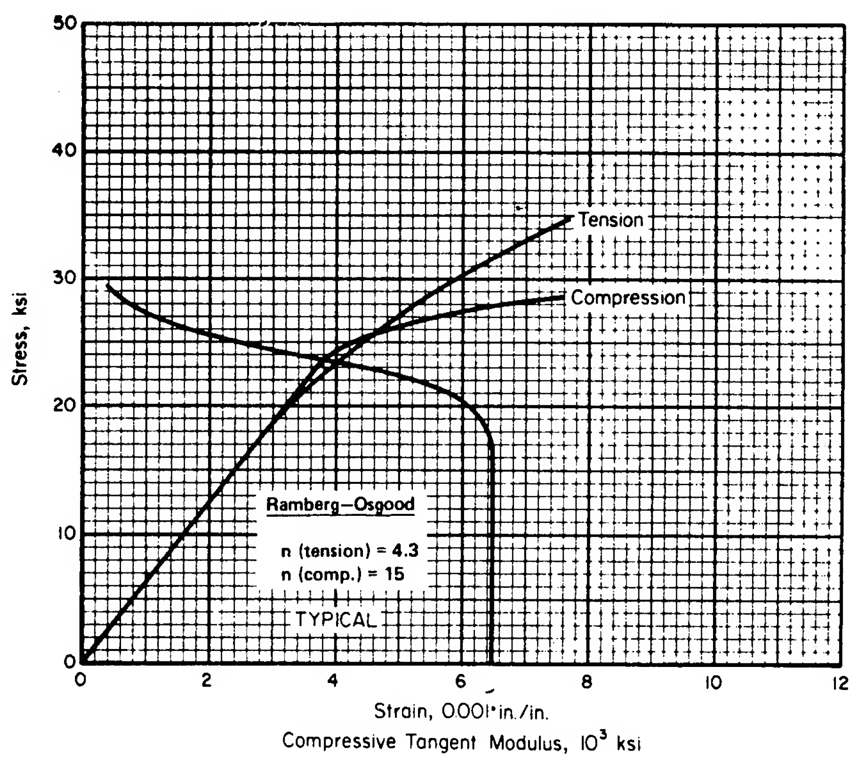

FIGURE 4.2.1.2.6. *Typical tensile and compressive stress-strain and compressive tangent-modulus curves for AZ31B-H24 sheet at room temperature.*

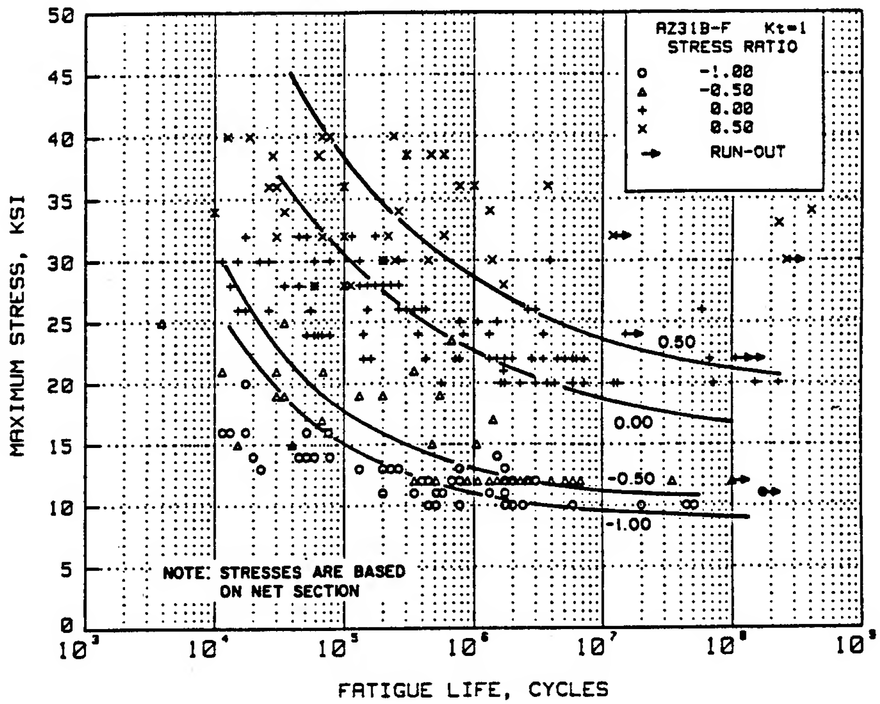

FIGURE 4.2.1.4.8(a) *Best-fit S/N curves for unnotched AZ31B-F magnesium alloy forged disk, transverse direction.*

Correlative Information for Figure 4.2.1.4.8(a)

Product Form: Forged disk, one-inch thick

Properties:	TUS, ksi	TYS, ksi	Temp., F
	38	26	RT

Specimen Details: Unnotched
0.75-inch gross diameter
0.30-inch net diameter

Surface Condition:

Polished sequentially with No. 320 aluminum oxide cloth, No. 0, 00 and 000 emery paper and finally No. 600 aluminum oxide powder in water

Reference: 4.2.1.1.8

Test Parameters:

Loading—Axial
Frequency—1500 cpm
Temperature—RT
Environment—Air

No. of Heats/Lots: 1

Equivalent Stress Equation:

For R values between −1.0 and −0.50
$\text{Log } N_f = 7.13\text{-}2.20 \log (S_{eq}\text{-}12.9)$
$S_{eq} = S_{max}(1\text{-}R)^{0.56}$
Standard Error of Estimate = 0.613
Standard Deviation of Life = 0.916
$R^2 = 55.2\%$
For R values between 0.0 and 0.50
$\text{Log } N_f = 8.87\text{-}3.26 \log (S_{eq}\text{-}15.0)$
$S_{eq} = S_{max}(1\text{-}R)^{0.33}$
Standard Error of Estimate = 0.829
Standard Deviation of Life = 1.014
$R^2 = 33.2\%$

Sample Size = 194

[Caution: The equivalent stress method may provide unrealistic life predictions for stress ratios beyond those represented above]

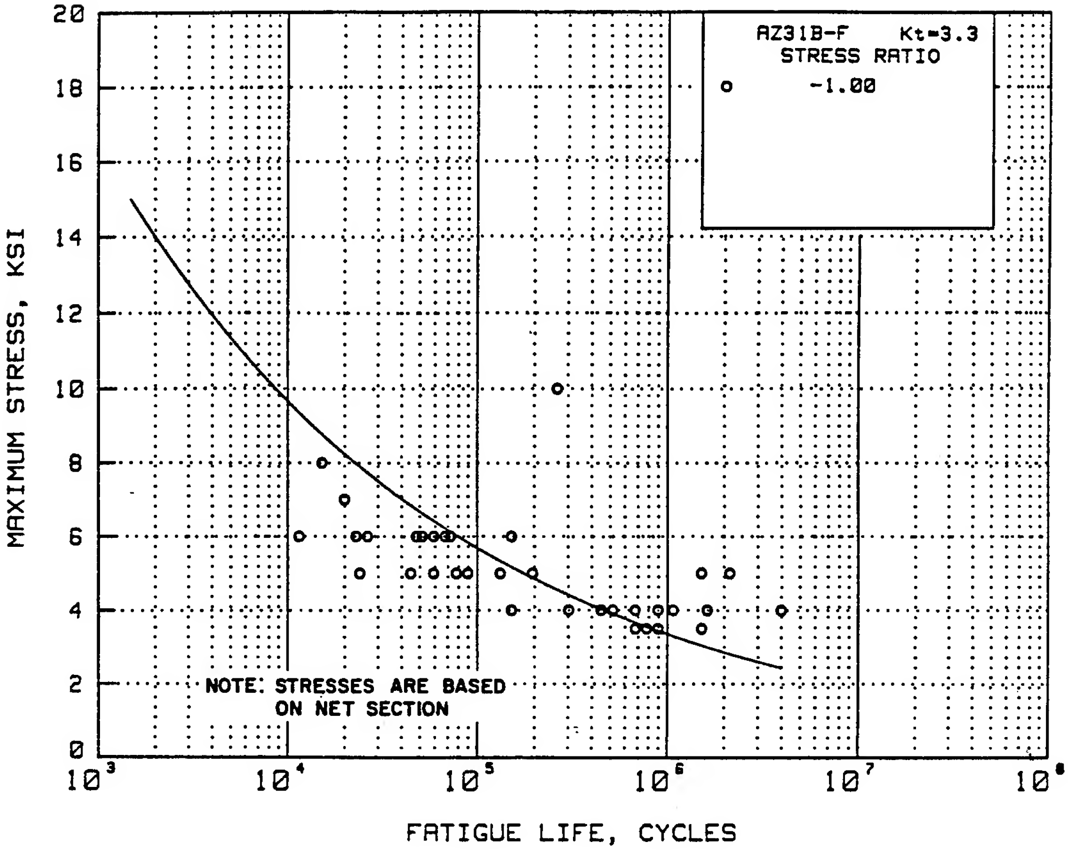

FIGURE 4.2.1.4.8(b) *Best-fit S/N curves for notched, K_t = 3.3, AZ31B-F magnesium alloy forged disk, transverse direction.*

Correlative Information for Figure 4.2.1.4.8(b)

Product Form: Forged disk, one-inch thick

Properties:	TUS, ksi	TYS, ksi	Temp., F
	38	26	RT

Specimen Details: Notched, K_t = 3.3
0.350-inch gross diameter
0.280-inch net diameter
0.01-inch root radius, r
60° flank angle, ω

Reference: 4.2.1.1.8

Test Parameters:

Loading—Axial
Frequency—1500 cpm
Temperature—RT
Environment—Air

No. of Heats/Lots: 1

Equivalent Stress Equation:

Log N_f = 8.28-4.34 log (S_{max})
Standard Error of Estimate = 0.534
Standard Deviation of Life = 0.707
R^2 = 43%

Sample Size = 34

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4.2.2 AZ61A

4.2.2.0 *Comments and Properties.*—AZ61A is a wrought magnesium-base alloy containing aluminum and zinc. It is available in the form of extruded sections, tubes, and forgings in the as-fabricated (F) temper. AZ61A is much like AZ31B in general characteristics. The increased aluminum content increases the strength and decreases the ductility slightly.

Severe forming must be done at elevated temperatures. This alloy is readily welded but must be stress relieved after welding to prevent stress corrosion cracking.

Material specifications covering AZ61A are given in Table 4.2.2.0(a). Room-temperature mechanical and physical properties are shown in Table 4.2.2.0(b).

TABLE 4.2.2.0(a). *Material Specifications for AZ61A Magnesium Alloy*

Specification	Form
AMS 4350	Extrusion
QQ-M-40	Forging

TABLE 4.2.2.0(b). *Design Mechanical and Physical Properties of AZ61A Magnesium Alloy Extrusion and Forging*

Specification	AMS 4350					QQ-M-40
Form	Extruded bar, rod, and solid shapes			Extruded hollow shapes	Extruded tube	Forging
Temper	F					
Thickness, in.	≤0.249	0.250-2.499	2.500-4.499[a]	All	0.028-0.750[b]	...
Basis	S	S	S	S	S	S
Mechanical Properties:						
F_{tu}, ksi:						
L	38	40	40	36	36	38
LT	...	...	...	...	...	...
F_{ty}, ksi:						
L	21	24	22	16	16	22
LT	...	...	...	...	...	...
F_{cy}, ksi:						
L	14	14	14	11	11	14
LT	...	...	...	...	...	...
F_{su}, ksi	19	19	...	...	...	19
F_{bru}[c], ksi:						
(e/D = 1.5)	45	45	...	...	...	50
(e/D = 2.0)	55	55	...	...	...	60
F_{bry}[c], ksi:						
(e/D = 1.5)	28	28	...	...	...	28
(e/D = 2.0)	32	32	...	...	...	32
e, percent:						
L	8	9	7	7	7	6
E, 10^3 ksi	6.3					
E_c, 10^3, ksi	6.3					
G, 10^3, ksi	2.4					
μ	0.31					
Physical Properties:						
ω, lb/in.^{3}	0.0647					
C, Btu/(lb)(F)	0.25 (at 78 F)[d]					
K, Btu/[(hr)(ft^2)(F)/ft]	46 (212 to 572 F)					
α, 10^{-6} in./in./F	14 (65 to 212 F)					

[a]For cross-sectional area ≤25 square inches.
[b]Wall thickness for outside diameters ≤6.000 inches.
[c]Bearing values are "dry pin" values per Section 1.4.7.1.
[d]Estimated.

4.2.3 ZK60A

4.2.3.0 *Comments and Properties.*—ZK60A is a wrought magnesium-base alloy containing zinc and zirconium. It is available as extruded sections, tubes, and forgings. Increased strength is obtained by artificial aging (T5) from the as-fabricated (F) temper. ZK60A has the best combination of high room-temperature strength and ductility of the wrought magnesium-base alloys. It is used primarily at temperatures below 300 F.

ZK60A has good ductility as compared with other high-strength magnesium alloys and can be formed or bent cold into shapes not possible with those alloys having less ductility. It is not considered a weldable alloy.

Material specifications for ZK60A are given in Table 4.2.3.0(a). Room-temperature mechanical and physical properties are shown in Tables 4.2.3.0(b) and (c). Elevated temperature curves for physical properties are shown in Figures 4.2.3.0.

TABLE 4.2.3.0(a). *Material Specifications for ZK60A Magnesium Alloy*

Specification	Form
ASTM B 107	Extrusion
AMS 4352	Extrusion
AMS 4362	Die and hand forgings

The temper index for ZK60A is as follows:

Section	Temper
4.2.3.1	F
4.2.3.2	T5

4.2.3.1 *ZK60A-F Temper.*

4.2.3.2 *ZK60A-T5 Temper.*—Typical room-temperature tension and compression stress-strain curves for extrusions are shown in Figures 4.2.3.2.6(a) and (b). Fatigue curves are presented in Figure 4.2.3.2.8(a) through (c).

TABLE 4.2.3.0(b). *Design Mechanical and Physical Properties of ZK60A Magnesium Alloy Extrusion*

Specification	ASTM B 107					
Form	Extruded rod, bar, and solid shapes				Extruded hollow shapes	Extruded tube
Temper	F					
Cross-sectional area, in.^{2}	<2.000	2.000-2.999	3.000-4.999	5.000-39.999	All	$\leq$3.000 in. O.D.
Thickness, in.	All	All	All	All	All	0.028-0.750 wall
Basis	S	S	S	S	S	S
Mechanical Properties:						
F_{tu}, ksi:						
L	43	43	43	43	40	40
LT	...	...	...	...	...	...
F_{ty}, ksi:						
L	31	31	31	31	28	28
LT	...	...	...	...	...	...
F_{cy}, ksi:						
L	27	26	25	20	20	20
LT	...	...	...	...	...	...
F_{su}, ksi	22	22	22	...	...	...
F_{bru}[a], ksi:						
(e/D = 1.5)	...	...	...	...	...	...
(e/D = 2.0)	70	70	70	...	...	...
F_{bry}[a], ksi:						
(e/D = 1.5)	...	...	...	...	...	...
(e/D = 2.0)	45	45	45	...	...	...
e, percent:						
L	5	5	5	4	5	5
E, 10^3 ksi	6.5					
E_c, 10^3, ksi	6.5					
G, 10^3, ksi	2.4					
μ	0.35					
Physical Properties:						
ω, lb/in.^{3}	0.0659					
C, K, and α	See Figure 4.2.3.0					

[a]Bearing values are "dry pin" values per Section 1.4.7.1.

TABLE 4.2.3.0(c). *Design Mechanical and Physical Properties of ZK60A Magnesium Alloy Extrusion and Forging*

Specification	AMS 4352									AMS 4362	
Form	Extruded rod, bar, and solid shapes						Extruded hollow shapes	Extruded Tube		Die Forging	Hand Forging
Temper	T5										
Cross-sectional area, in.^{2}	<2.000	2.000-2.999	3.000-4.999	5.000-9.999	10.000-24.999	25.000-39.999	All	$\leq$3.000 in. O.D.	3.000-8.500 in. O.D.	...	...
Thickness, in.	All	All	All	All	All	All	All	0.028-0.250 wall	0.094-1.188 wall	$\leq$3.000	$\leq$6.000
Basis	S	S	S	S	S	S	S	S	S	S	S
Mechanical Properties:											
F_{tu}, ksi:											
L	45	45	45	45	45	43	46	46	44	42	38
LT	...	...	...	...	...	...	...	...	...	...	...
F_{ty}, ksi:											
L	36	36	36	34	34	31	38	38	33	26	20
LT	...	...	...	...	...	...	...	...	...	...	...
F_{cy}, ksi:											
L	30	28	25	23	22	20	26	26	21	...	...
LT	...	...	...	...	...	...	...	...	...	...	...
F_{su}, ksi	22	22	22	...	...	...	...	...	...	...	...
F_{bru}[a], ksi:											
(e/D = 1.5)	...	...	...	...	...	...	...	...	...	...	...
(e/D = 2.0)	71	71	71	...	...	...	...	...	...	...	...
F_{bry}[a], ksi:											
(e/D = 1.5)	...	...	...	...	...	...	...	...	...	...	...
(e/D = 2.0)	47	47	47	...	...	...	...	...	...	...	...
e, percent:											
L	4	4	4	6	6	6	4	4	4	7	7
E, 10^3 ksi	6.5										
E_c, 10^3, ksi	6.5										
G, 10^3, ksi	2.4										
μ	0.35										
Physical Properties:											
ω, lb/in.^{3}	0.0659										
C, K, and α	See Figure 4.2.3.0										

[a]Bearing values are "dry pin" values per Section 1.4.7.1.

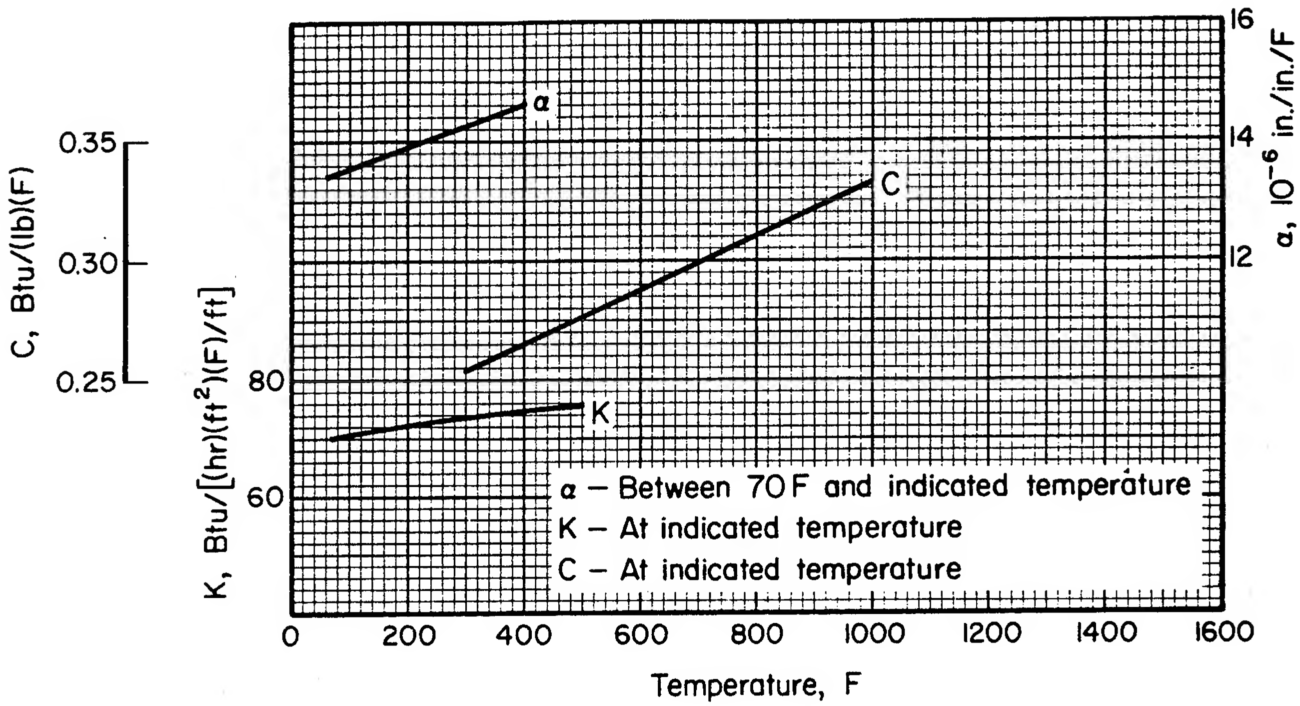

FIGURE 4.2.3.0. *Effect of temperature on the physical properties of ZK60A magnesium alloy.*

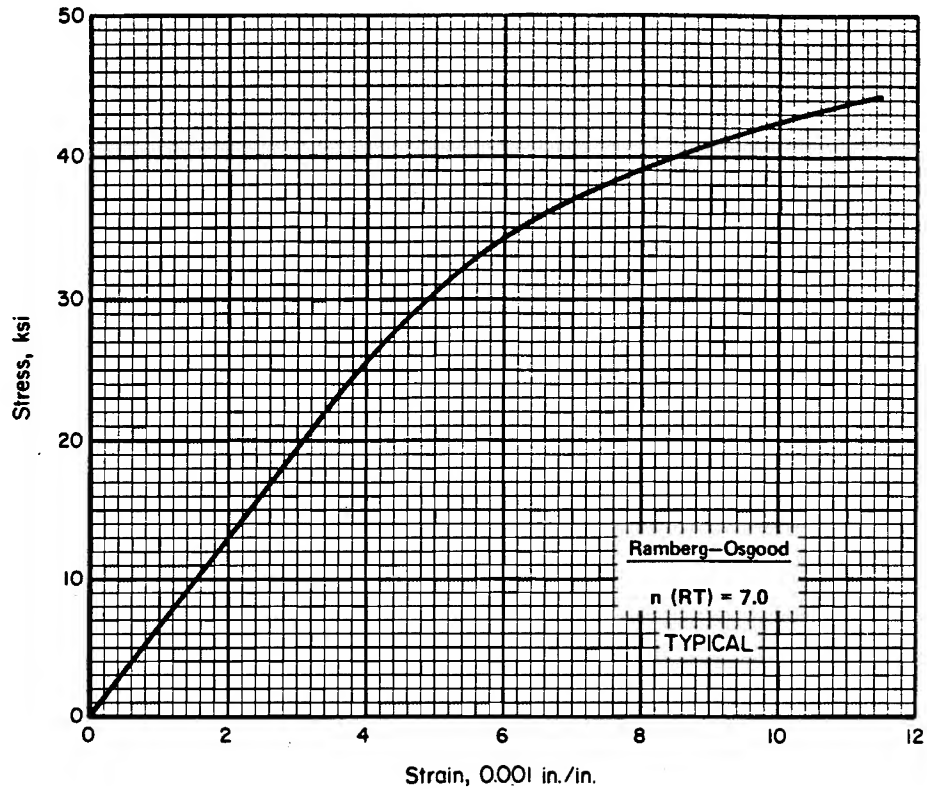

FIGURE 4.2.3.2.6(a). *Typical tensile stress-strain curve for ZK60A-T5 extrusion at room temperature.*

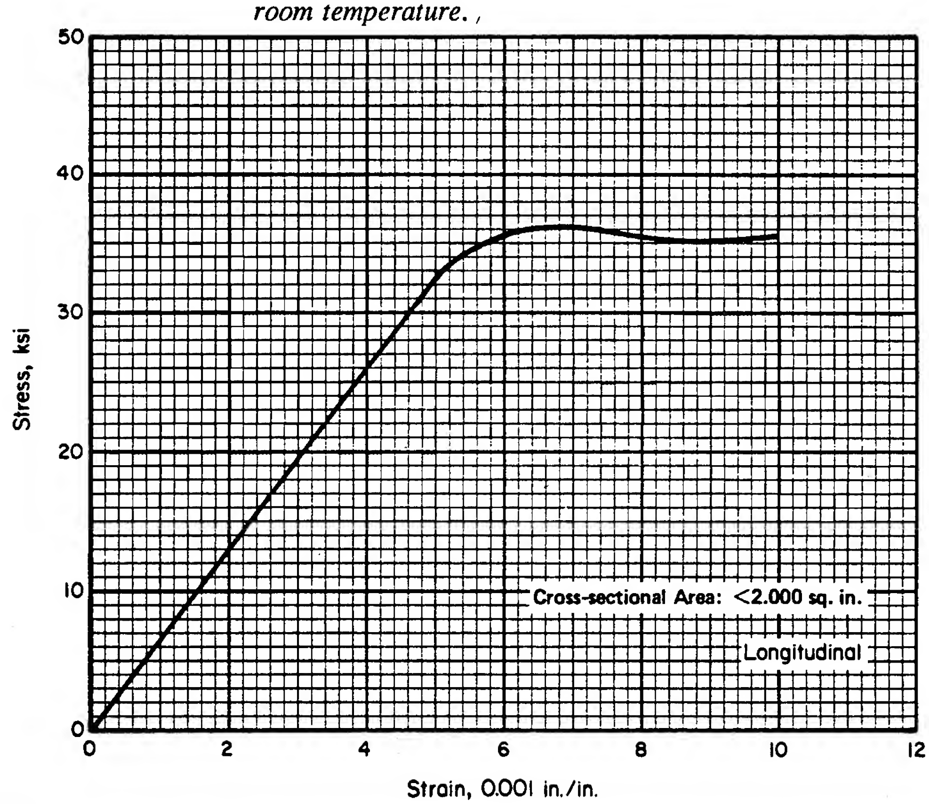

FIGURE 4.2.3.2.6(b). *Typical compressive stress-strain curve for ZK60A-T5 extrusion at room temperature.*

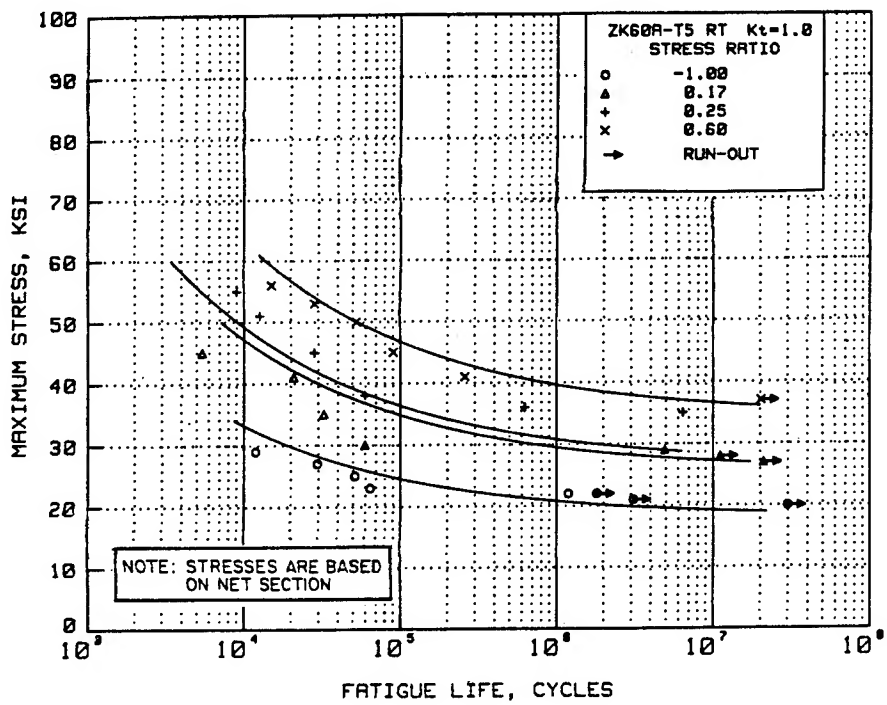

FIGURE 4.2.3.2.8(a). *Best-fit S/N curves for unnotched ZK60A-T5 extruded bar, longitudinal direction.*

Correlative Information for Figure 4.2.3.2.8(a)

Product Form: Extruded bar, 0.50-inch diameter

Properties:

TUS, ksi	TYS, ksi	Temp., F
47.5	40.9	RT (unnotched)

Specimen Details: Unnotched
0.50-inch gross diameter
0.40-inch net diameter
0.750-inch root diameter
7.50-inch long

Surface Condition: Polished with No. 240 grit aluminum oxide belt and then a No. 400 grit; polished with kerosene to better than 10 micro-inches

Reference: 4.2.3.2.8

Test Parameters:
Loading - Axial
Frequency - 3600 cpm
Temperature - RT
Environment - Air

No. of Heats/Lots: Not specified

Equivalent Stress Equation
$\text{Log } N_f = 7.56 - 2.73 \log (S_{eq} - 23.7)$
$S_{eq} = S_{max} (1-R)^{0.40}$
Standard Error of Estimate = 0.60
Standard Deviation in Life = 0.85
$R^2 = 51\%$

Sample Size = 21

[Caution: The equivalent stress model may provide unrealistic life predictions for stress ratios beyond those represented above]

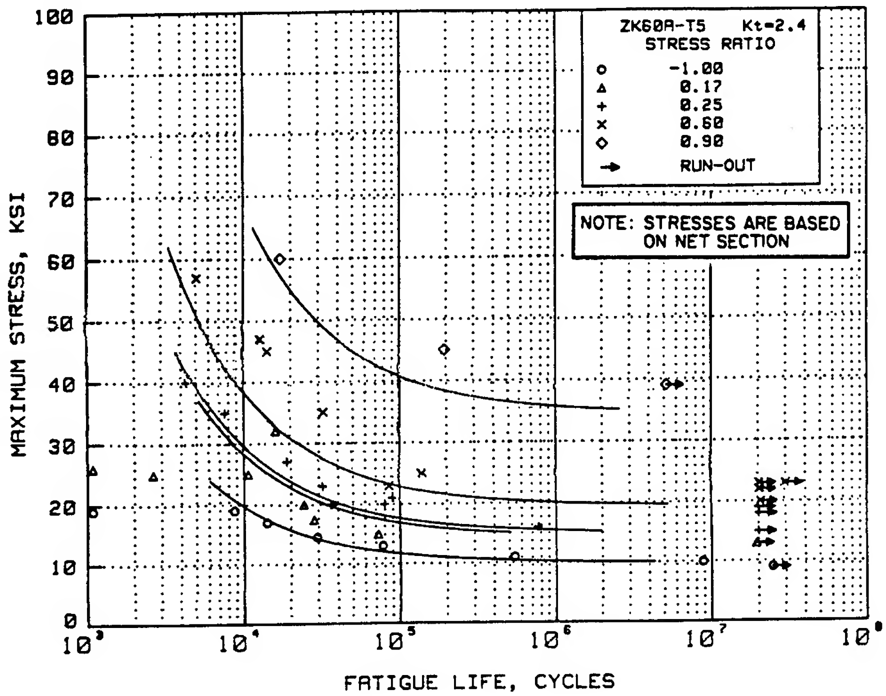

FIGURE 4.2.3.2.8(b). *Best-fit S/N curves for notched, K_t = 2.4, ZK60A-T5 extruded bar, longitudinal direction.*

Correlative Information for Figure 4.2.3.2.8(b)

Product Form: Extruded bar, 0.50-inch diameter

Properties:	TUS, ksi	TYS, ksi	Temp., F
	63.7	40.9	RT
			(notched)

Specimen Details: Circumferential notched, $K_t = 2.4$
0.50-inch gross diameter
0.40-inch net diameter
0.032-inch notch radius
60° flank angle, ω

Surface Condition: Ground with aluminum oxide wheel lubricated with sulfur cutting oil; lapped with a copper rod and No. 600 grit alundum lapping compound

Reference: 4.2.3.2.8

Test Parameters:
Loading - Axial
Frequency - 3600 cpm
Temperature - RT
Environment - Air

No. of Heats/Lots: Not specified

Equivalent Stress Equation
$\text{Log } N_f = 5.51 - 1.36 \log (S_{eq} - 13.2)$
$S_{eq} = S_{max} (1-R)^{0.42}$
Standard Error of Estimate = 0.46
Standard Deviation in Life = 0.82
R^2 = 69%

Sample Size = 30

[Caution: The equivalent stress model may provide unrealistic life predictions for stress ratios beyond those represented above]

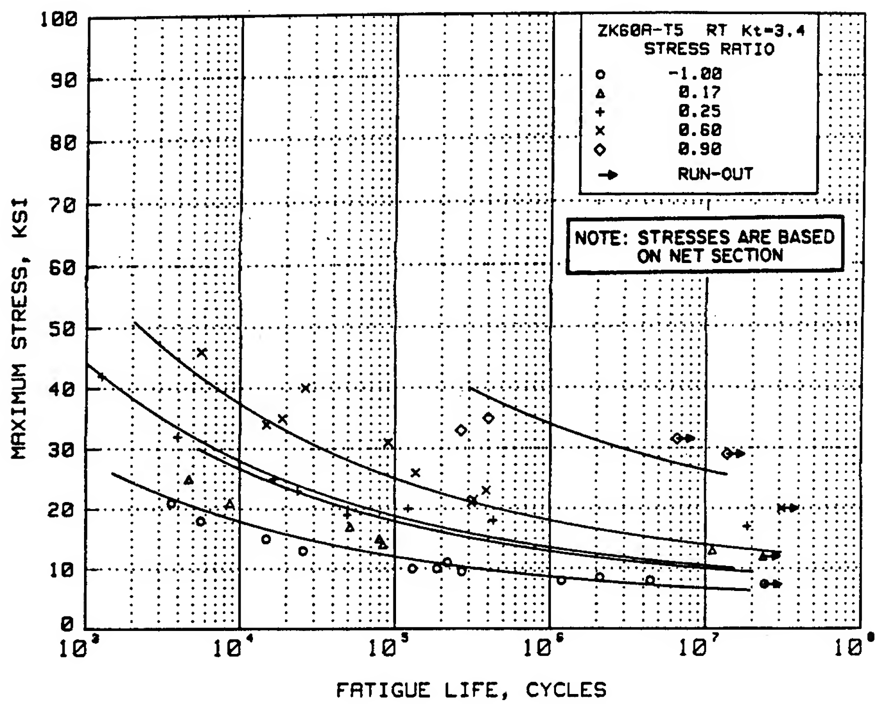

FIGURE 4.2.3.2.8(c). *Best-fit S/N curves for notched, $K_t = 3.4$, ZK60A-T5 extruded bar, longitudinal direction.*

Correlative Information for Figure 4.2.3.2.8(c)

Product Form: Extruded bar, 0.50-inch diameter

Properties:	TUS, ksi	TYS, ksi	Temp., F
	58.2	40.9	RT (notched)

Specimen Details: Circumferential notched, $K_t = 3.4$
0.50-inch gross diameter
0.40-inch net diameter
0.010-inch notch radius
60° flank angle, ω

Surface Condition: Ground with aluminum oxide wheel lubricated with sulfur cutting oil; lapped with a copper rod and No. 600 grit alundum lapping compound

Reference: 4.2.3.2.8

Test Parameters:
Loading - Axial
Frequency - 3600 cpm
Temperature - RT
Environment - Air

No. of Heats/Lots: Not specified

Equivalent Stress Equation
$\text{Log } N_f = 9.27 - 4.13 \log (S_{eq} - 5.3)$
$S_{eq} = S_{max} (1-R)^{0.46}$
Standard Error of Estimate = 0.55
Standard Deviation in Life = 0.99
$R^2 = 70\%$

Sample Size = 36

[Caution: The equivalent stress model may provide unrealistic life predictions for stress ratios beyond those represented above]

4.3 Magnesium Cast Alloys

4.3.1 AM100A

4.3.1.0 *Comments and Properties.*—AM100A is a magnesium-base casting alloy containing aluminum and a small amount of manganese. It is primarily used as permanent mold castings. AM100A has about the same characteristics as AZ92A. AM100A has less tendency to microshrinkage and hot shortness than the Mg-Al-Zn alloys. It has good weldability and fair pressure tightness.

Material specifications for AM100A are given in Table 4.3.1.0(a). Room-temperature mechanical and physical properties are shown in Table 4.3.1.0(b).

TABLE 4.3.1.0(a). *Material Specifications for AM100A Magnesium Alloy*

Specification	Form
AMS 4455	Investment casting
AMS 4483	Permanent mold casting
MIL-M-46062	Casting

TABLE 4.3.1.0(b). *Design Mechanical and Physical Properties of AM100A Magnesium Alloy Casting*

Specification	AMS 4455	AMS 4483	MIL-M-46062			
Form	Investment casting	Permanent mold casting	Casting (any method)			
Temper	T6	T6	T6			
Location within casting	Any area		Designated area			Nondesignated area
			Class 1[b]	Class 2[b]	Class 3[b]	
Basis	S	S	S	S	S	S
Mechanical Properties[a]:						
F_{tu}, ksi	17[c]	17[c]	38	35	30	17
F_{ty}, ksi	9.5[c]	10[c]	20	18	16	10
F_{cy}, ksi	9.5	10	20	18	16	10
F_{su}, ksi	...	...	...	...	...	...
F_{bru}, ksi:						
(e/D = 1.5)	...	...	...	...	...	...
(e/D = 2.0)	...	...	...	...	...	...
F_{bry}, ksi:						
(e/D = 1.5)	...	...	...	...	...	...
(e/D = 2.0)	...	...	...	...	...	...
e, percent	...	...	3	1.5	1	0.75
E, 10^3 ksi	6.5					
E_c, 10^3 ksi	6.5					
G, 10^3 ksi	2.4					
μ	0.35					
Physical Properties:						
ω, lb./in.^{3}	0.0651					
C, K, and α	...					

[a]Reference should be made to the specific requirements of the procuring or certificating agency with regard to the use of the above values in the design of castings.
[b]Class of properties attainable depends on location specified and casting design and should be coordinated with the producer.
[c]When specified on drawing, conformance to tensile property requirements is determined by testing specimens cut from castings.

4.3.2 AZ91C/AZ91E

4.3.2.0 *Comments and Properties.*—AZ91C is a magnesium-base casting alloy containing aluminum and zinc. AZ91E is a version which contains a significantly lower level of impurities resulting in improved corrosion resistance. These alloys have good castability with a good combination of ductility and strength. AZ91C and AZ91E are the most commonly used sand castings for temperatures under 300 F. AZ91C is available as sand and investment castings, while AZ91E is available as a sand casting. AZ91C and AZ91E have fair weldability and pressure tightness.

Some material specifications covering AZ91C/AZ91E are presented in Table 4.3.2.0(a). Room-temperature mechanical and physical properties are shown in Tables 4.3.2.0(b) and (c).

TABLE 4.3.2.0(a). *Material Specifications for AZ91C/AZ91E Magnesium Alloy*

Specification	Form
AMS 4437	Sand casting
AMS 4452	Investment casting
MIL-M-46062	Casting
AMS 4446	Sand casting

The temper index for AZ91C/AZ91E is as follows:

Section	Temper
4.3.2.1	T6

4.3.2.1 *T6 Temper.*—Figure 4.3.2.1.4 contains an elevated temperature curve for tension and compression moduli. Typical tensile stress-strain curves at room temperature and several elevated temperatures are presented in Figure 4.3.2.1.6.

TABLE 4.3.2.0(b). *Design Mechanical and Physical Properties of AZ91C Magnesium Alloy Casting*

Specification	AMS 4437	AMS 4452	MIL-M-46062			
Form	Sand casting	Investment casting	Casting (any method)			
Temper	T6	T6	T6			
Location within casting	Any area		Designated area			Nondesignated area
			Class 1[b]	Class 2[b]	Class 3[b]	
Basis	S	S	S	S	S	S
Mechanical Properties[a]:						
F_{tu}, ksi	17[c]	17[c]	35	29	27	17
F_{ty}, ksi	12[c]	12[c]	18	16	14	12
F_{cy}, ksi	12	12	18	16	14	12
F_{su}, ksi	...	...	...	...	...	...
F_{bru}, ksi:						
(e/D = 1.5)	...	...	...	...	...	...
(e/D = 2.0)	...	...	...	...	...	...
F_{bry}, ksi:						
(e/D = 1.5)	...	...	...	...	...	...
(e/D = 2.0)	...	...	...	...	...	...
e, percent	0.75[c]	...	4	3	2	0.75
E, 10^3 ksi	6.5					
E_c, 10^3 ksi	6.5					
G, 10^3 ksi	2.4					
μ	0.35					
Physical Properties:						
ω, lb./in.^{3}	0.0652					
C, Btu/(lb)(F)	0.25[d]					
K, Btu/[(hr)(ft^2)(F)/ft]	41 (212 F to 572 F)					
α, 10^{-6} in./in./F	14 (65 F to 212 F)					

[a]Reference should be made to the specific requirements of the procuring or certificating agency with regard to the use of the above values in the design of castings.
[b]Class of properties attainable depends on location specified and casting design and should be coordinated with the producer.
[c]When specified on drawing, conformance to tensile property requirements is determined by testing specimens cut from castings.
[d]Estimated.

TABLE 4.3.2.0(c). *Design Mechanical and Physical Properties of AZ91E Magnesium Alloy Casting*

Specification	AMS 4446
Form	Sand casting
Condition	T6
Location within casting	Any area
Basis	S
Mechanical Properties[a]:	
F_{tu}, ksi	17[b]
F_{ty}, ksi	12[b]
F_{cy}, ksi	12
F_{su}, ksi	...
F_{bru}, ksi:	
(e/D = 1.5)	...
(e/D = 2.0)	...
F_{bry}, ksi:	
(e/D = 1.5)	...
(e/D = 2.0)	...
e, percent	...
E, 10^3 ksi	6.5
E_c, 10^3, ksi	6.5
G, 10^3, ksi	2.4
μ	0.35
Physical Properties:	
ω, lb/in.^{3}	0.0652
C, Btu/(lb)(F)	0.25[c]
K, Btu/[(hr)(ft^2)(F)/ft]	41 (212 F to 572 F)
α, 10^{-6} in./in./F	14 (65 F to 212 F)

[a]Reference should be made to the specific requirements of the procuring or certificating agency with regard to the use of the above values in the design of castings.
[b]When specified on drawing, conformance to tensile property requirements is determined by testing specimens cut from castings.
[c]Estimated.

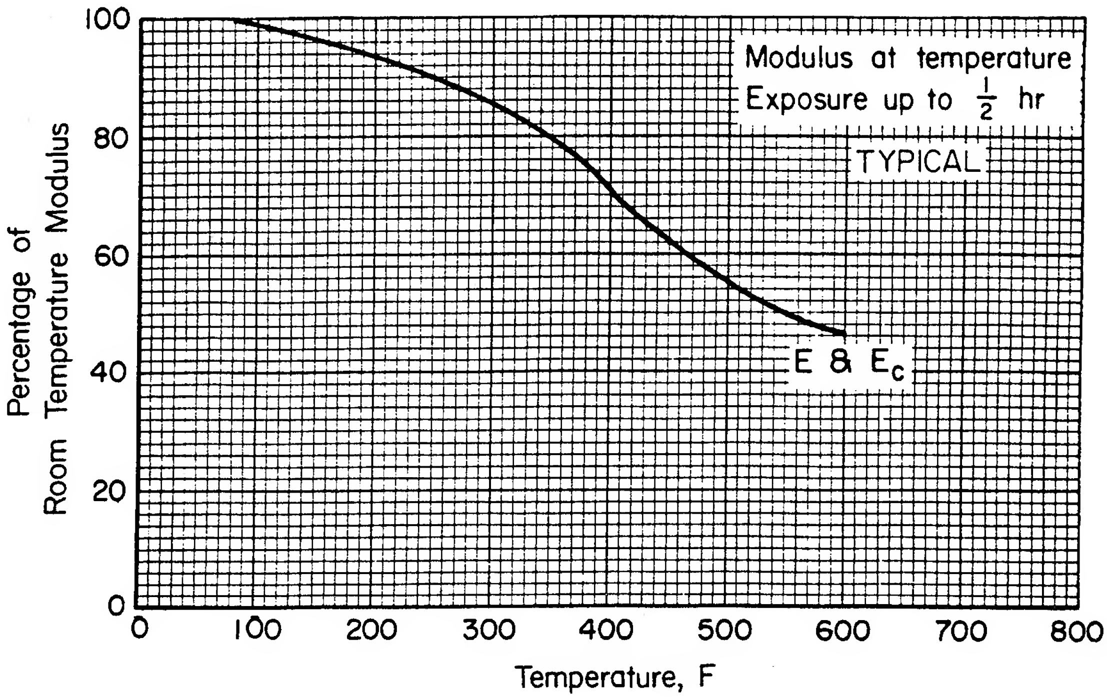

FIGURE 4.3.2.1.4. *Effect of temperature on the tensile and compressive moduli (E and E_c) of cast AZ91C-T6/AZ91E-T6.*

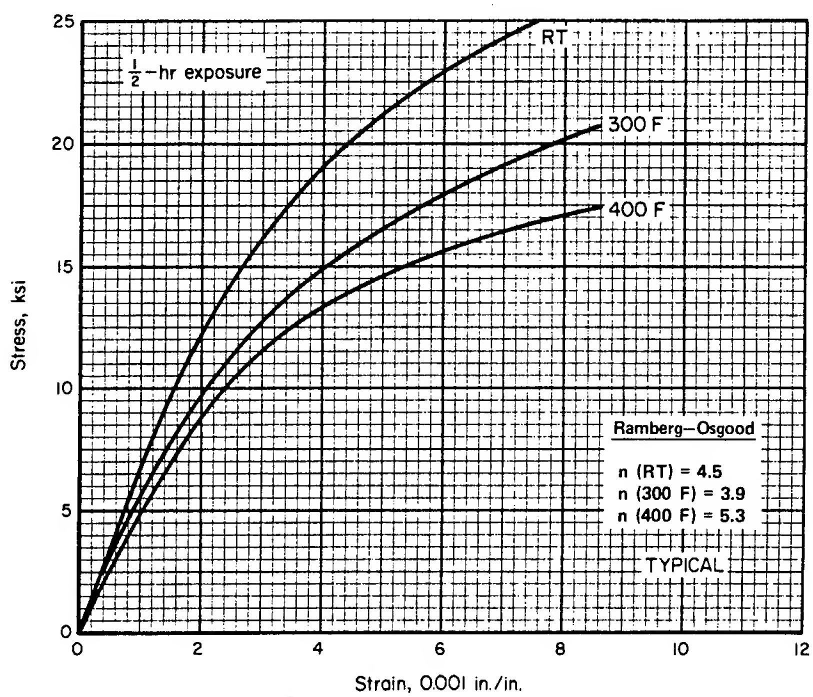

FIGURE 4.3.2.1.6. *Typical tensile stress-strain curves for cast AZ91C-T6/AZ91E-T6 at room and elevated temperatures.*

4.3.3 AZ92A

4.3.3.0 *Comments and Properties.*—AZ92A is a magnesium-base casting alloy containing aluminum and zinc. It is slightly stronger and less ductile than AZ91C but is much like it in other characteristics. It is available as sand and permanent-mold casting. AZ92A has fair weldability and pressure tightness.

Material specifications for AZ92A are presented in Table 4.3.3.0(a). Room-temperature mechanical and physical properties are shown in Table 4.3.3.0(b). Elevated temperature curves for physical properties are shown in Figure 4.3.3.0.

TABLE 4.3.3.0(a). *Material Specifications for AZ92A Magnesium Alloy*

Specification	Form
AMS 4434	Sand casting
AMS 4484	Permanent-mold casting
MIL-M-46062	Casting

The temper index for AZ92A is as follows:

Section	Temper
4.3.3.1	T6

4.3.3.1 *AZ92A-T6 Temper.*—Elevated temperature curves for various mechanical properties are presented in Figures 4.3.3.1.1(a) through (c), and 4.3.3.1.4. Typical stress-strain and tangent-modulus curves at room temperature and several elevated temperatures are shown in Figures 4.3.3.1.6(a) and (b).

TABLE 4.3.3.0(b). *Design Mechanical and Physical Properties of AZ192A Magnesium Alloy Casting*

Specification	AMS 4484	AMS 4434	MIL-M-46062			
Form	Permanent mold casting	Sand casting	Casting (any method)			
Temper	T6	T6	T6			
Location within casting	Any area		Designated area			Nondesignated area
			Class 1[b]	Class 2[b]	Class 3[b]	
Basis	S	S	S	S	S	S
Mechanical Properties[a]:						
F_{tu}, ksi	17[c]	17[c]	40	34	30	17
F_{ty}, ksi	13.5[c]	13.5[c]	25	20	18	13
F_{cy}, ksi	13.5	13.5[c]	25	20	18	13
F_{su}, ksi	...	...	...	...	...	...
F_{bru}, ksi:						
(e/D = 1.5)	...	...	...	...	...	...
(e/D = 2.0)	...	...	...	...	...	...
F_{bry}, ksi:						
(e/D = 1.5)	...	...	...	...	...	...
(e/D = 2.0)	...	...	...	...	...	...
e, percent	...	...	3	1	0.75	0.50
E, 10^3 ksi	6.5					
E_c, 10^3 ksi	6.5					
G, 10^3 ksi	2.4					
μ	0.35					
Physical Properties:						
ω, lb./in.^{3}	0.0659					
C, Btu/(lb)(F)	0.25[d]					
K and α	See Figure 4.3.3.0					

[a]Reference should be made to the specific requirements of the procuring or certificating agency with regard to the use of the above values in the design of castings.
[b]Class of properties attainable depends on location specified and casting design and should be coordinated with the producer.
[c]When specified on drawing, conformance to tensile property requirements is determined by testing specimens cut from castings.
[d]Estimated.

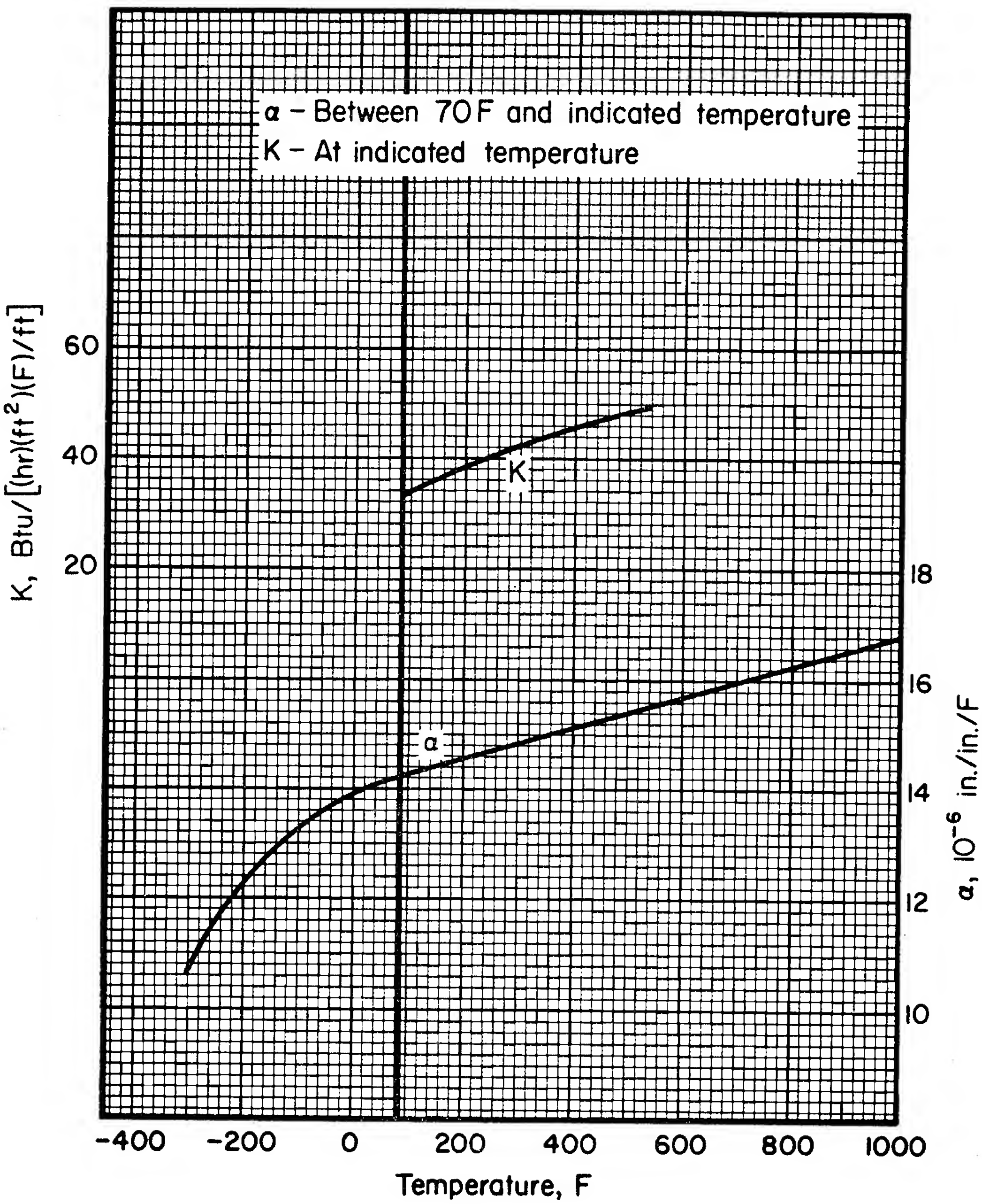

FIGURE 4.3.3.0. *Effects of temperature on the physical properties of cast AZ92A-T6.*

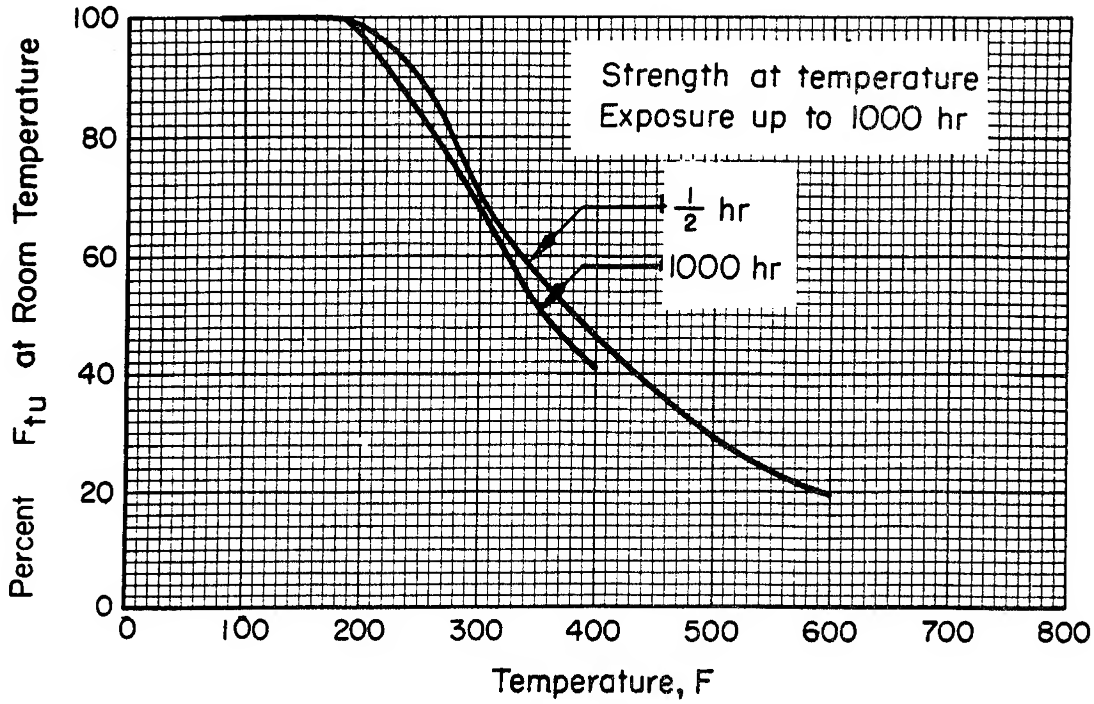

FIGURE 4.3.3.1.1(a). *Effect of temperature on the tensile ultimate strength (F_{tu}) of cast AZ92A-T6.*

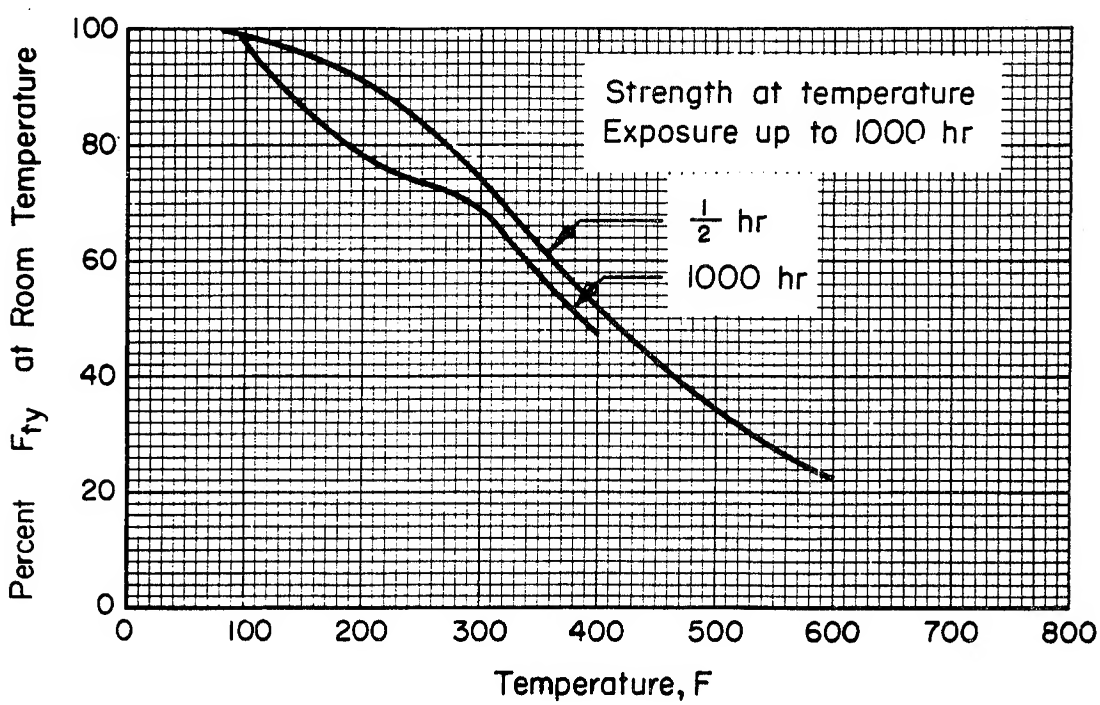

FIGURE 4.3.3.1.1(b). *Effect of temperature on the tensile yield strength (F_{ty}) of cast AZ92A-T6.*

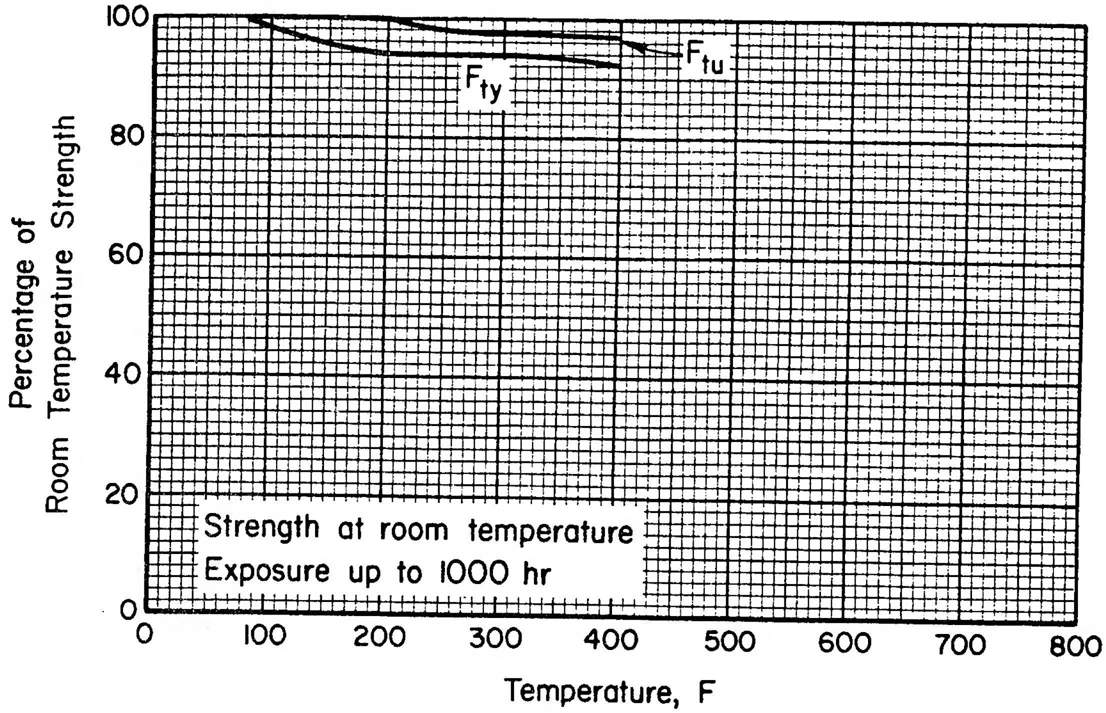

FIGURE 4.3.3.1.1(c). *Effect of exposure at elevated temperature on the room-temperature tensile ultimate strength (F_{tu}) and the tensile yield strength (F_{ty}) of cast AZ92A-T6.*

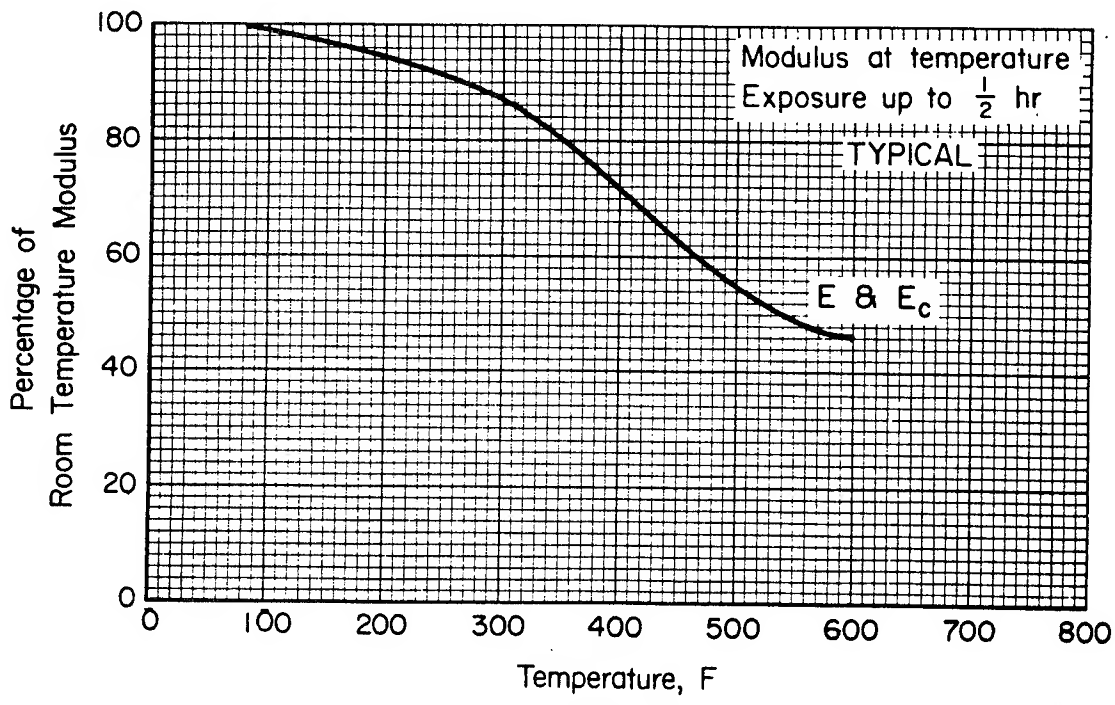

FIGURE 4.3.3.1.4. *Effect of temperature on the tensile and compressive moduli (E and E_c) of cast AZ92A-T6.*

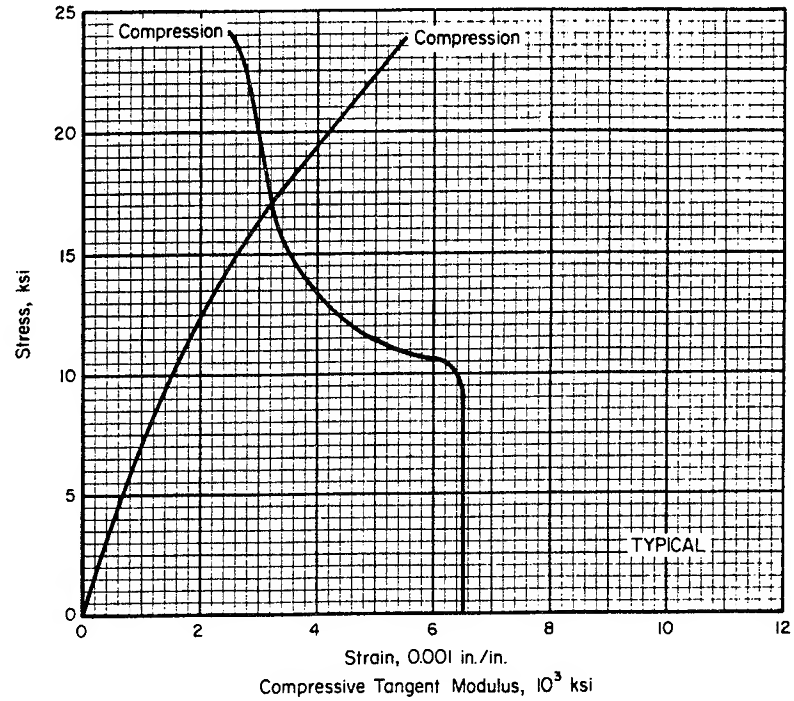

FIGURE 4.3.3.1.6(a). *Typical compressive stress-strain and compressive tangent-modulus curves for cast AZ92A-T6 at room temperature.*

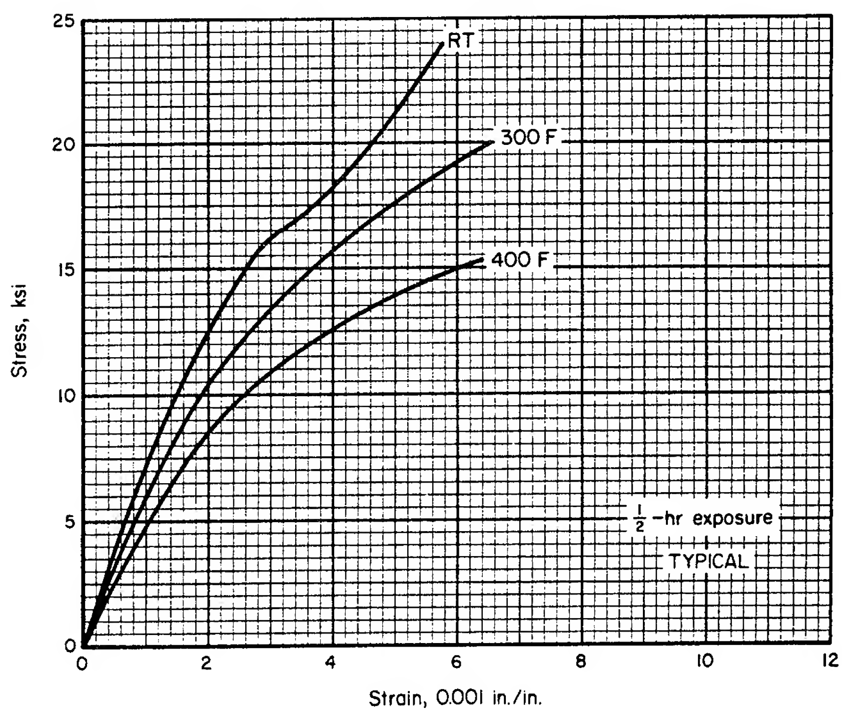

FIGURE 4.3.3.1.6(b). *Typical tensile stress-strain curves for cast AZ92A-T6 at room and elevated temperatures.*

4.3.4 EZ33A

4.3.4.0 *Comments and Properties.*—EZ33A is a magnesium-base casting alloy containing rare earths, zinc, and zirconium. It is available as sand castings in the artificially aged (T5) temper. EZ33A has lower strength than the Mg-Al-Zn alloys at room temperature but is less affected by increasing temperature. It is generally used for applications at temperatures of 300 to 500 F. EZ33A castings are very sound and are sometimes used for pressure tightness. It has good stability in the T5 temper and excellent weldability. It is sometimes used for applications requiring good damping ability.

A material specification for EZ33A is presented in Table 4.3.4.0(a). Room-temperature mechanical and physical properties are shown in Table 4.3.4.0(b). The effect of temperature on physical properties is shown in Figure 4.3.4.0.

TABLE 4.3.4.0(a). *Material Specification for EZ33A Magnesium Alloy*

Specification	Form
AMS 4442	Sand casting

The temper index for EZ33A is as follows:

Section	Temper
4.3.4.1	T5

4.3.4.1 *EZ33A-T5 Temper.*—Elevated temperature curves for tensile properties are presented in Figures 4.3.4.1.1(a) through (c). A typical tensile stress-strain curve at room temperature is presented in Figure 4.3.4.1.6.

TABLE 4.3.4.0(b). *Design Mechanical and Physical Properties of EZ33A Magnesium Alloy Casting*

Specification	AMS 4442
Form	Sand casting
Temper	T5
Location within casting	Any area
Basis	S
Mechanical Properties[a]:	
F_{tu}, ksi	13[b]
F_{ty}, ksi	11[b]
F_{cy}, ksi	11
F_{su}, ksi	...
F_{bru}, ksi:	
(e/D = 1.5)	...
(e/D = 2.0)	...
F_{bry}, ksi:	
(e/D = 1.5)	...
(e/D = 2.0)	...
e, percent	1.5
E, 10^3 ksi	6.5
E_c, 10^3 ksi	6.5
G, 10^3 ksi	2.4
μ	0.35
Physical Properties:	
ω, lb/in.^{3}	0.0659
C, Btu/(lb)(F)	0.25
K and α	See Figure 4.3.4.0

[a] Reference should be made to the specific requirements of the procuring or certificating agency with regard to the use of the above values in the design of castings.
[b] When specified on drawing, conformance to tensile property requirements is determined by testing specimens cut from castings.

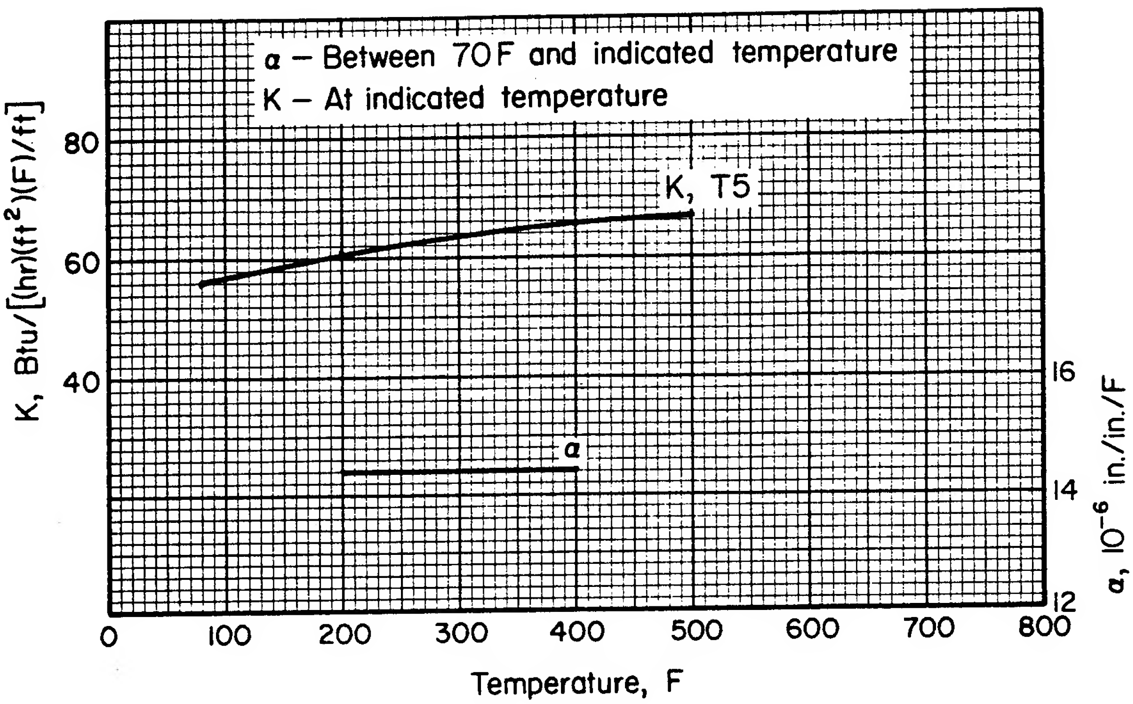

FIGURE 4.3.4.0. *Effect of temperature on the physical properties of cast EZ33A.*

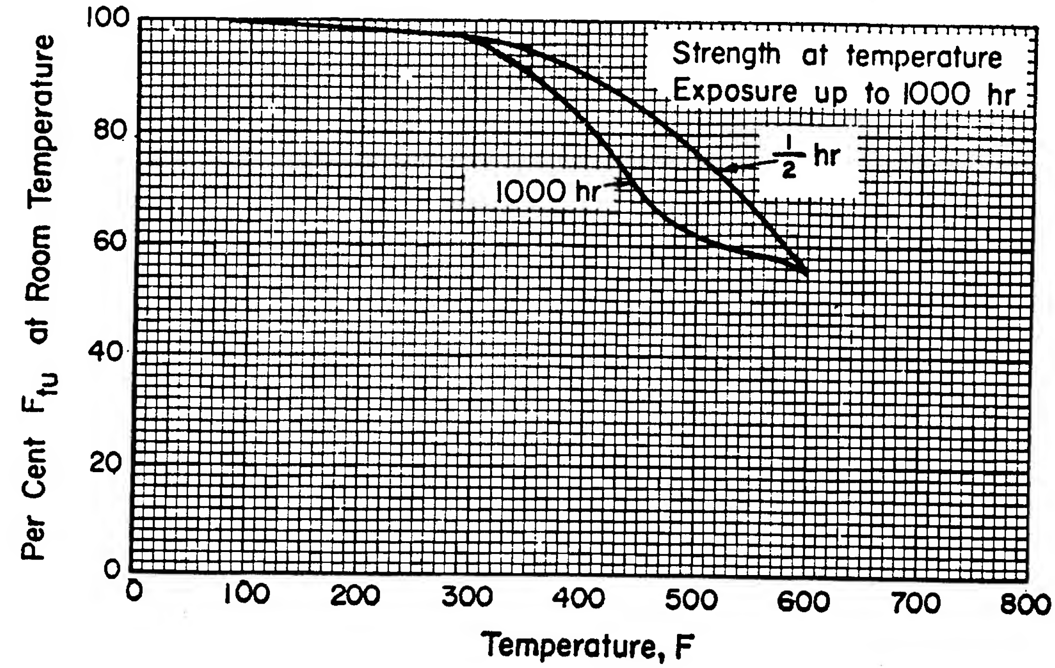

FIGURE 4.3.4.1.1(a). *Effect of temperature on the ultimate tensile strength of (F_{tu}) of cast EZ33A-T5.*

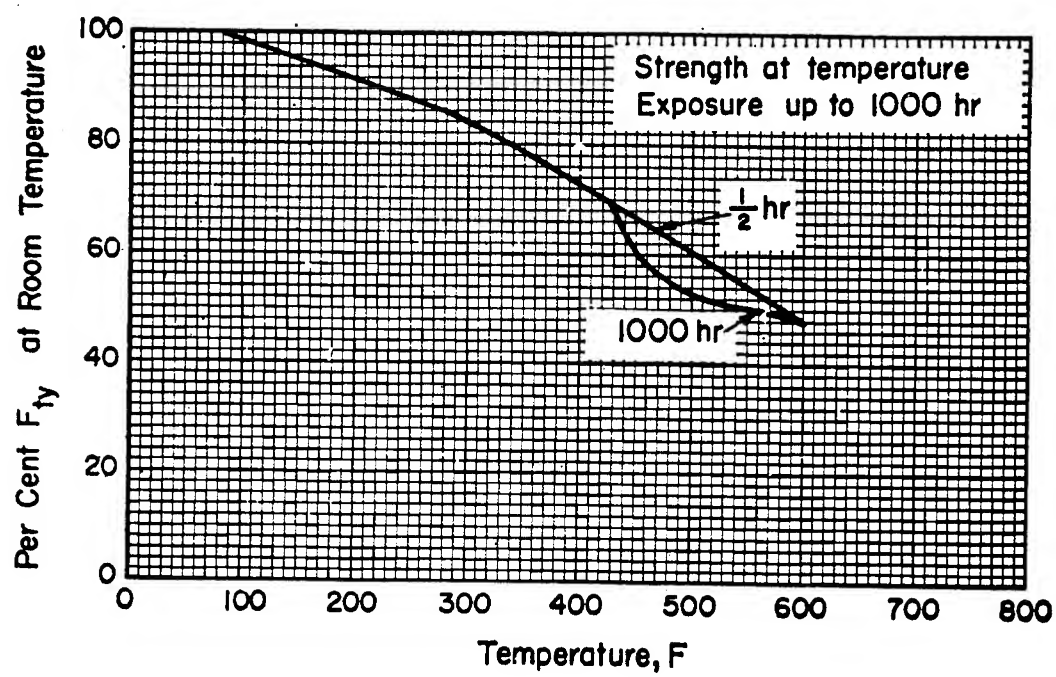

FIGURE 4.3.4.1.1(b). *Effect of temperature on the tensile yield strength (F_{ty}) of cast EZ33A-T5.*

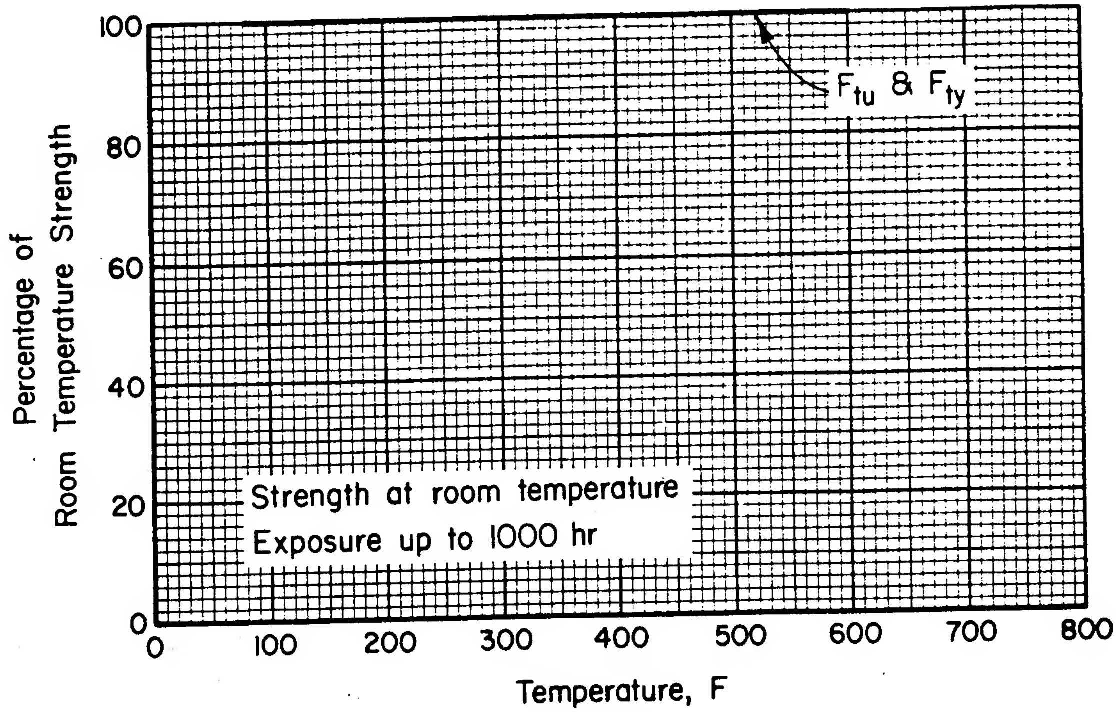

FIGURE 4.3.4.1.1(c). *Effect of exposure at elevated temperatures on the room temperature tensile ultimate strength (F_{tu}) and the tensile yield strength (F_{ty}) of cast EZ33A-T5.*

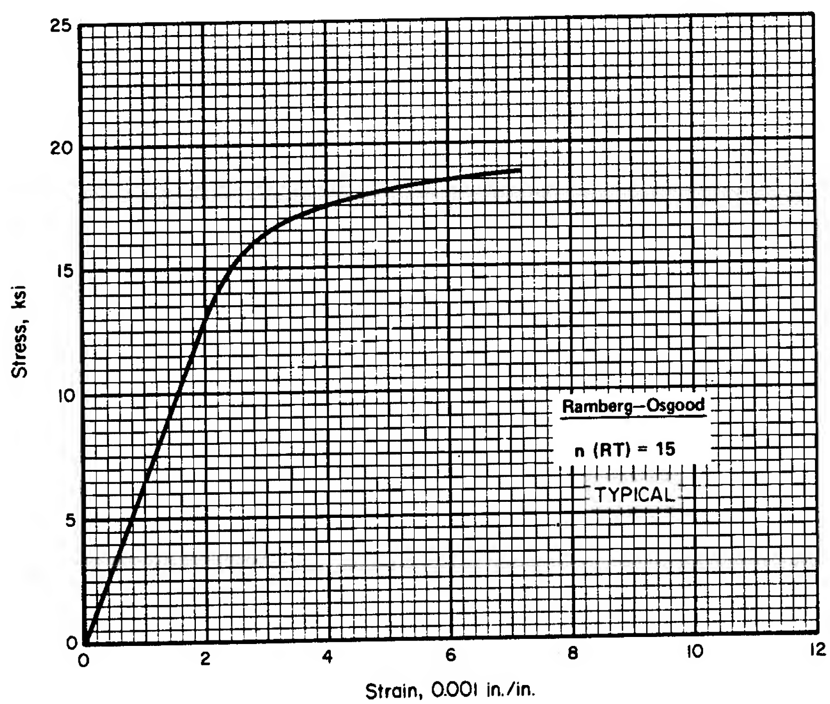

FIGURE 4.3.4.1.6. *Typical tensile stress-strain curve for cast EZ33A-T5 at room temperature.*

4.3.5 QE22A

4.3.5.0 *Comments and Properties.*—QE22A is a magnesium-base alloy containing silver, rare earths in the form of didymium, and zirconium. It is available as sand and permanent-mold castings. It is used in the solution heat-treated and artificially aged (T6) condition where a high yield strength is needed at temperatures up to 600 F. QE22A has good weldability and fair pressure tightness.

Material specifications for QE22A are presented in Table 4.3.5.0(a). Room-temperature mechanical and physical properties are shown in Table 4.3.5.0(b).

TABLE 4.3.5.0(a). *Material Specifications for QE22A Magnesium Alloy*

Specification	Form
AMS 4418	Sand casting
MIL-M-46062	Casting

The temper index for QE22A is as follows:

Section	Temper
4.3.5.1	T6

4.3.5.1 *QE22A-T6 Temper.*—Elevated temperature curves for various tensile properties and modulus of elasticity are presented in Figures 4.3.5.1.1 and 4.3.5.1.4. Typical tensile stress-strain curves at various temperatures from room temperature through 700 F are shown in Figure 4.3.5.1.6.

TABLE 4.3.5.0(b). *Design Mechanical and Physical Properties of QE22A Magnesium Alloy Casting*

Specification	AMS 4418	MIL-M-46062			
Form	Sand casting	Casting (any method)			
Temper	T6				
Location within casting	Any area	Designated area			Nondesignated area
		Class 1[b]	Class 2[b]	Class 3[b]	
Basis	S	S	S	S	S
Mechanical Properties[a]:					
F_{tu}, ksi	28[c]	40	37	33	28
F_{ty}, ksi	20[c]	28	26	23	20
F_{cy}, ksi	20	28	26	23	20
F_{su}, ksi	...	...	...	...	...
F_{bru}, ksi:					
(e/D = 1.5)	...	...	...	...	...
(e/D = 2.0)	...	...	...	...	...
F_{bry}, ksi:					
(e/D = 1.5)	...	...	...	...	...
(e/D = 2.0)	...	...	...	...	...
e, percent	1[c]	4	2	2	1
E, 10^3 ksi	6.5				
E_c, 10^3 ksi	6.5				
G, 10^3 ksi	2.4				
μ	0.35				
Physical Properties:					
ω, lb/in.^{3}	0.0653				
C, Btu/(lb)(F)	0.25[d]				
K, Btu/[(hr)(ft^2)(F)/ft]	59				
α, 10^{-6} in./in./F	14 (68 F to 392 F)				

[a]Reference should be made to the specific requirements of the procuring or certificating agency with regard to the use of the above values in the design of castings.
[b]Class of properties attainable depends on location specified and casting design and should be coordinated with the producer.
[c]When specified on drawing, conformance to tensile property requirements is determined by testing specimens cut from castings.
[d]Estimated.

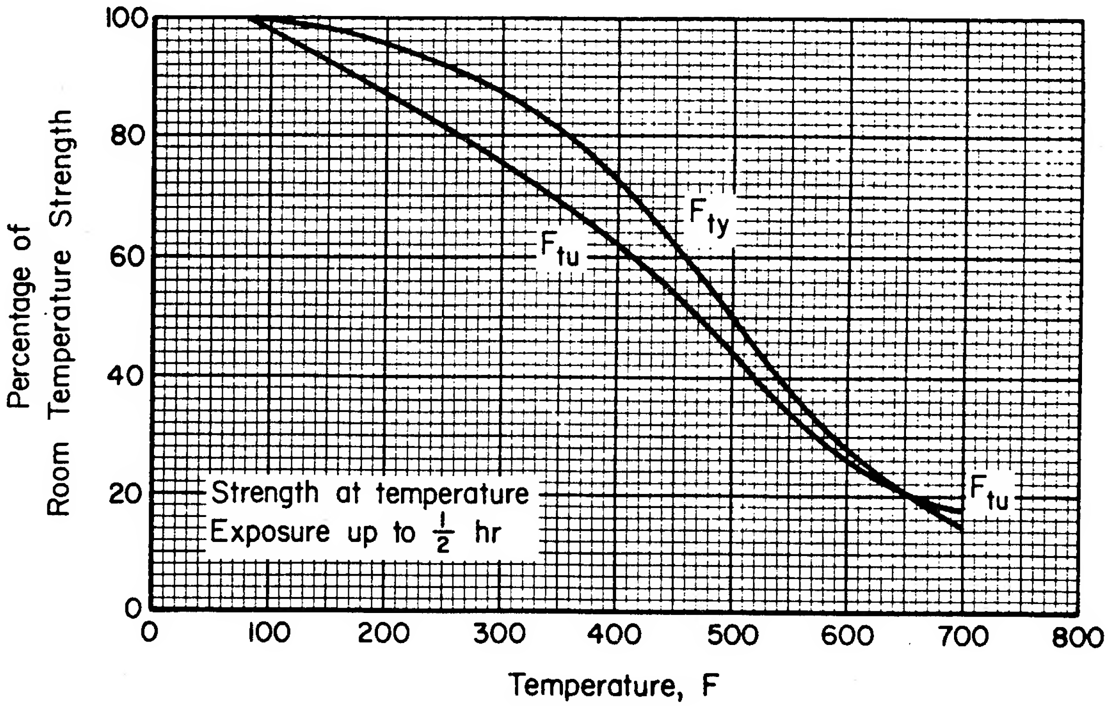

FIGURE 4.3.5.1.1. *Effect of temperature on the tensile ultimate strength (F_{tu}) and the tensile yield strength (F_{ty}) of cast QE22A-T6.*

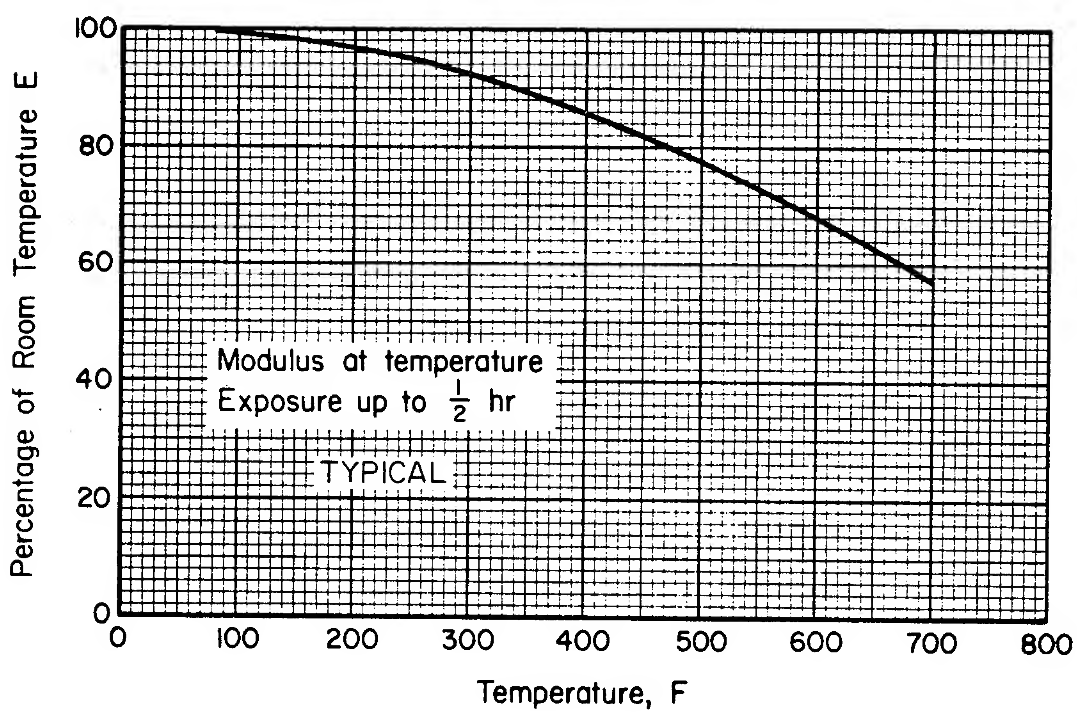

FIGURE 4.3.5.1.4. *Effect of temperature on the tensile modulus (E) of cast QE22A-T6.*

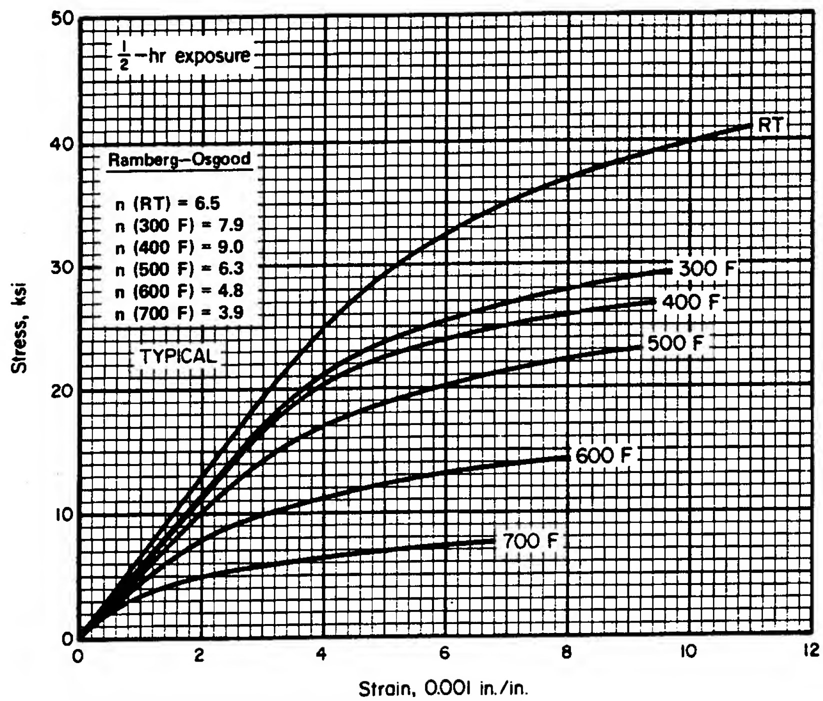

FIGURE 4.3.5.1.6. *Typical tensile stress-strain curves for cast QE22A-T6 at room and elevated temperatures.*

4.3.6 ZE41A

4.3.6.0 *Comments and Properties.*—ZE41A is a magnesium-base casting alloy containing zinc, zirconium, and rare earth elements. It is available as sand or permanent-mold castings in the artificially aged temper (T5). ZE41A has a higher yield strength than the Mg-Al-Zn alloys at room temperature and is more stable at elevated temperatures. It is useful for applications at temperatures up to 320 F. ZE41A castings posses good weldability and are pressure tight.

A material specification for ZE41A is presented in Table 4.3.6.0(a). Room temperature mechanical and physical properties are shown in Table 4.3.6.0(b). The effect of temperature on thermal conductivity is shown in Figure 4.3.6.0.

TABLE 4.3.6.0(a). *Material Specification for ZE41A Magnesium Alloy*

Specification	Form
AMS 4439	Sand casting

The temper index for ZE41A is as follows:

Section	Temper
4.3.6.1	T5

4.3.6.1 *T5 Temper.*—Elevated temperature curves for tensile yield and ultimate strengths are presented in Figure 4.3.6.1.1. The effect of temperature on the tensile modulus of elasticity is shown in Figure 4.3.6.1.4. Figures 4.3.6.1.6(a) and (b) contain tensile and compressive stress-strain curves as well as a compressive tangent-modulus curve.

TABLE 4.3.6.0(b). *Design Mechanical and Physical Properties of ZE41A Magnesium Alloy Casting*

Specification	AMS 4439
Form	Sand casting
Temper	T5
Thickness, in.	Any area
Basis	S
Mechanical Properties[a]:	
F_{tu}, ksi	26[b]
F_{ty}, ksi	17.5[b]
F_{cy}, ksi	15
F_{su}, ksi	17
F_{bru}, ksi:	
(e/D = 1.5)	38
(e/D = 2.0)	49
F_{bry}[c], ksi:	
(e/D = 1.5)	31
(e/D = 2.0)	35
e, percent	2[b]
E, 10^3 ksi	6.5
E_c, 10^3, ksi	6.5
G, 10^3, ksi	2.4
μ	0.35
Physical Properties:	
ω, lb/in.^{3}	0.0656
C, Btu/(lb)(F)	0.234 (at 68 F)
K, Btu/[(hr)(ft^2)(F)/ft]	See Figure 4.3.6.0
α, 10^{-6} in./in./F	1.5.5 (68 to 212 F)

[a] The mechanical properties shown are reliably obtainable when castings are produced under the quality assurance provisions of AMS 4439. These provisions require preproduction approval, documentation of foundry procedures, and specific testing procedures for the acceptance of each production lot of castings. Strict adherence to these requirements is mandatory if these properties are to be reliably assured in each casting.
[b] Conformance to tensile property requirements is determined by testing specimens cut from casting only when specified on drawing.
[c] Bearing values are "dry pin" values per Section 1.4.7.1.

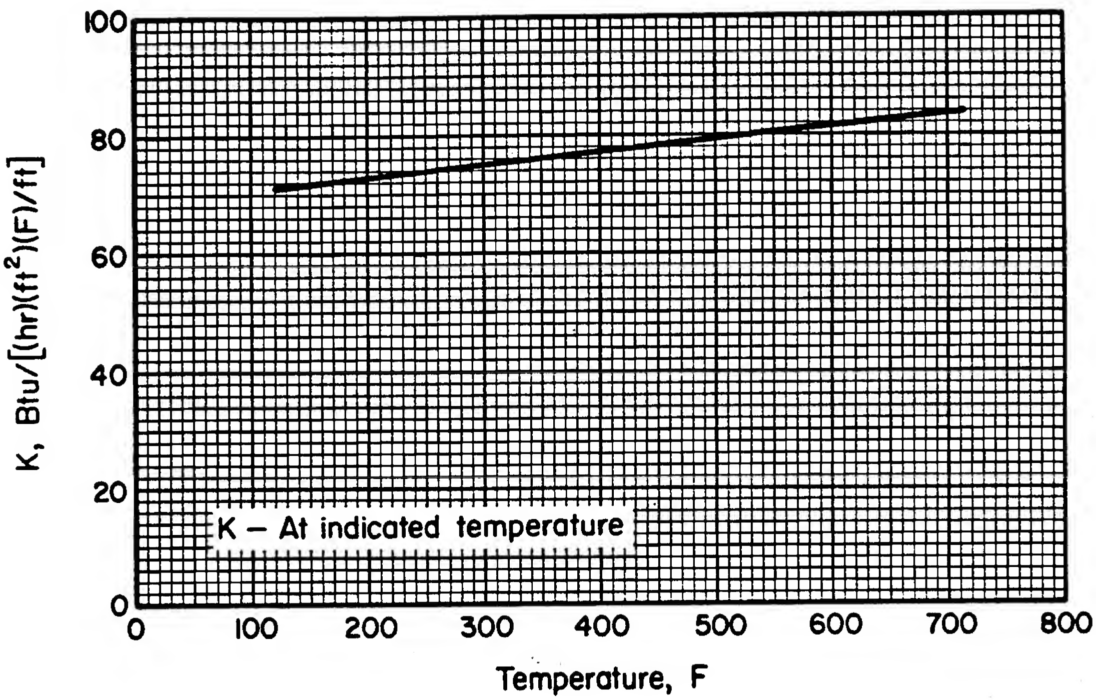

FIGURE 4.3.6.0. *Effect of temperature on the thermal conductivity (K) of ZE41A-T5 sand casting.*

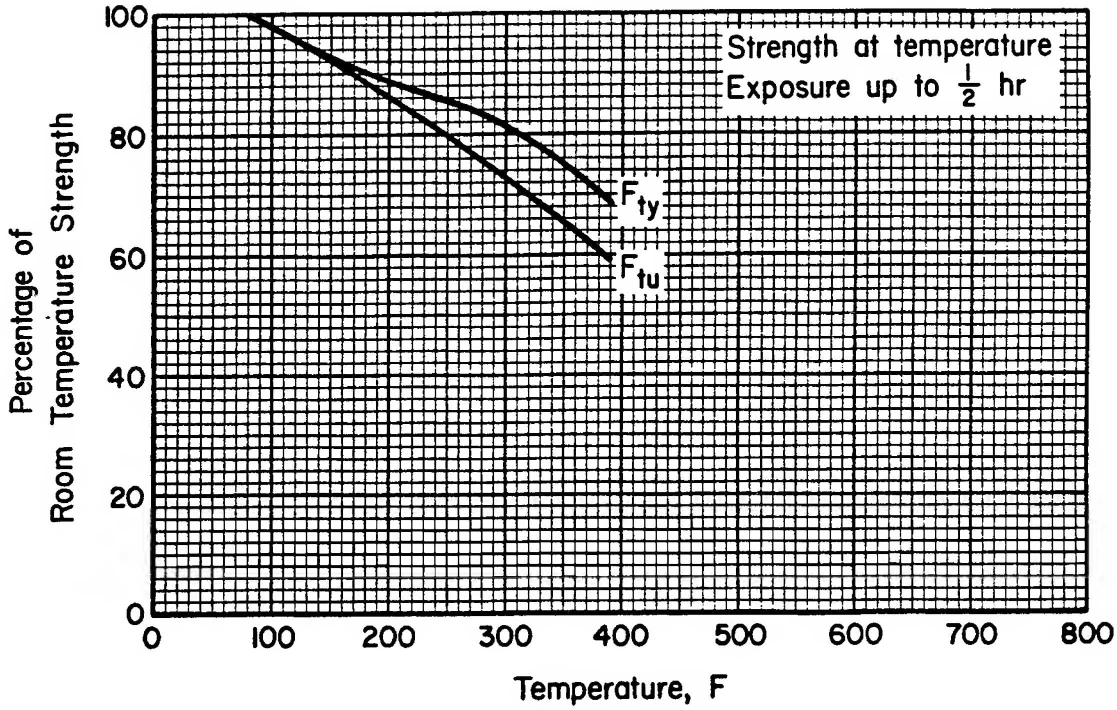

FIGURE 4.3.6.1.1. *Effect of temperature on the tensile ultimate strength (F_{tu}) and tensile yield strength (F_{ty}) of ZE41A-T5 sand casting.*

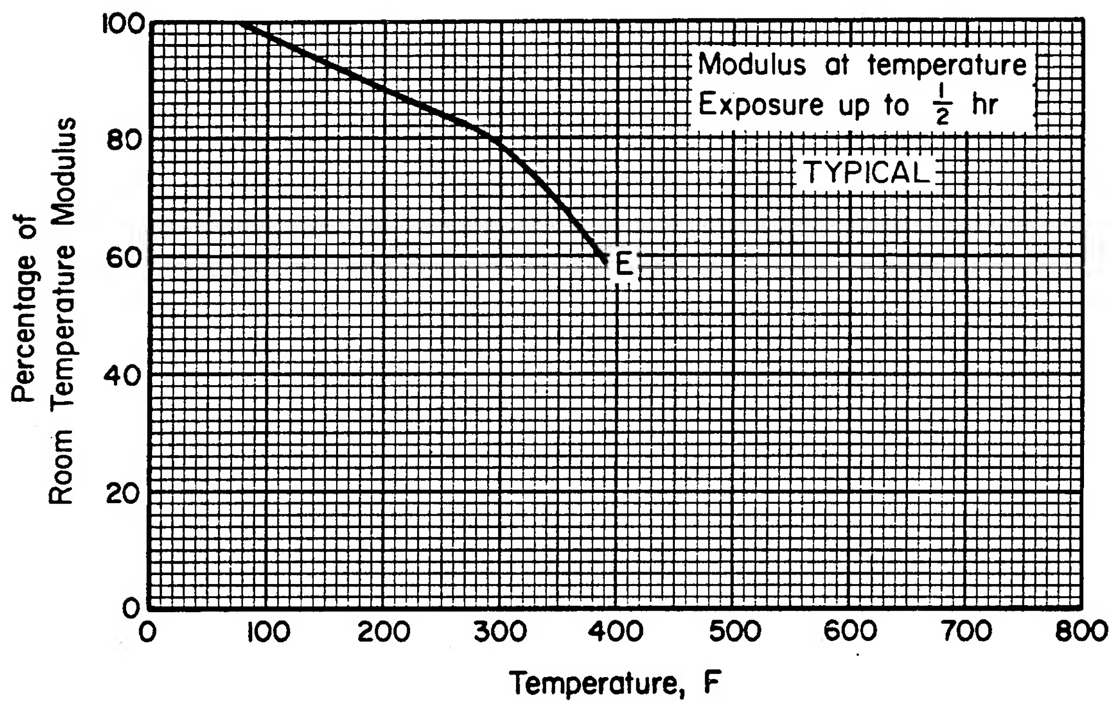

FIGURE 4.3.6.1.4. *Effect of temperature on the tensile modulus (E) of ZE41A-T5 sand casting.*

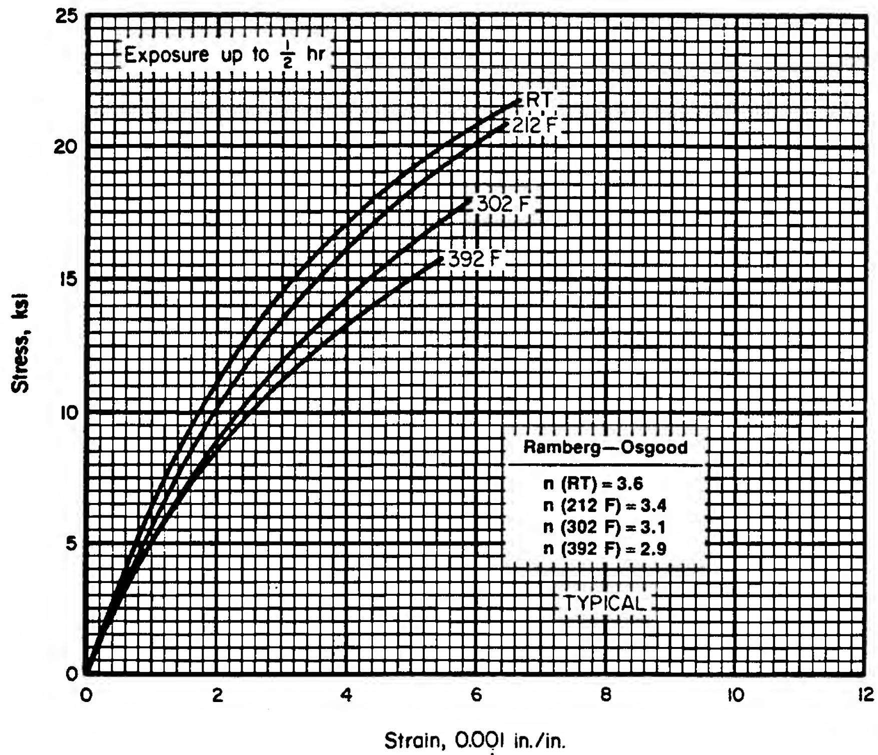

FIGURE 4.3.6.1.6(a). *Typical tensile stress-strain curves for ZE41A-T5 sand casting at room and elevated temperatures.*

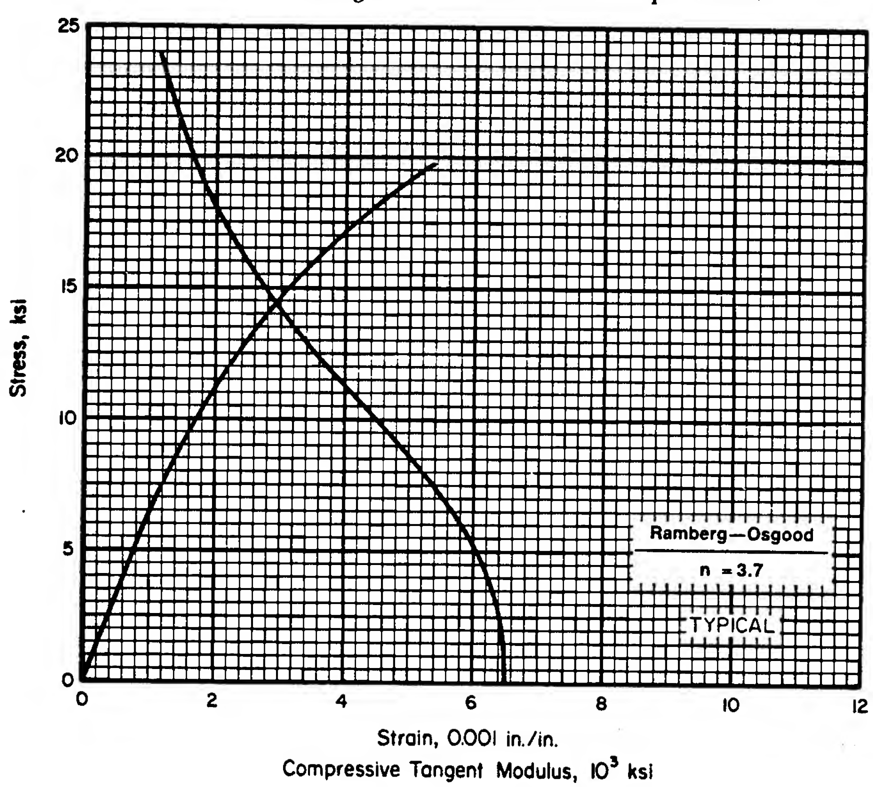

FIGURE 4.3.6.1.6(b). *Typical compressive stress-strain and tangent-modulus curves for ZE41A-T5 sand casting at room temperature.*

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4.4 Element Properties

4.4.1 BEAMS.—See Equation 1.3.2.1 in Section 1.5.2.5, and References 1.7.1(a) and (b) for general information on stress analysis of beams.

4.4.1.1 *Simple Beams.*—Beams of solid tubular, or similar cross sections can be assumed to fail through exceeding an allowable modulus of rupture in bending (F_b). In the absence of specific data, the ratio F_b/F_{tu} can be assumed to be 1.25 for solid sections.

4.4.1.1.1 *Round Tubes.*—For round tubes, the value of F_b will depend on the D/t ratio as well as the compressive yield stress.

4.4.1.1.2 *Unconventional Cross Sections.*—Sections other than solid or tubular should be tested to determine allowable bending stress.

4.4.1.2 *Built-up Beams.*—Built-up beams will usually fail because of local failure of component parts.

4.4.1.3 *Thin-Web Beams.*—The allowable stress for thin-web beams will depend on the nature of the failure and are determined from the allowable stress of the web in tension and of the flanges or stiffeners in compression.

4.4.2 COLUMNS

4.4.2.1 *Primary Failure.*—The general formula for primary instability is given in Section 1.3.8. Formulas applicable to magnesium-alloy columns are given in Tables 4.4.2.1(a) and (b). See References 4.4.2(a) and (b).

TABLE 4.4.2.1(a). *Column Formula for Magnesium-Alloy Extruded Open Shapes*

General Formula[a]

$$\frac{P}{A} = \frac{K(F_{cy})^n}{(L'/\rho)^m}$$

(Stress values are in ksi)

Alloy	K	n	M	Max. P/A
AZ31B, AZ61A	2,900	¼	1.5	F_{cy}
ZK60A-T5	3,300	¼	1.5	$0.96\ F_{cy}$

[a]Formula is for members that do not fail by local buckling. See Figure 4.4.2.3(a).

TABLE 4.4.2.1(b). *Column Formula for AZ31B-H24 Magnesium-Alloy Sheet*

$$\frac{P}{A} = 1.05\ F_{cy} - \frac{(1.05\ F_{cy})^2\ (L'/\rho)^2}{4\ \pi^2\ E}$$

$$\text{MAX}\ \frac{P}{A} = F_{cy}$$

See Figure 4.4.2.3.(b).

4.4.2.2 *Local Failure.*

4.4.2.3 *Column Properties.*—Curves of the allowable column stresses for various magnesium alloy columns are given in Figures 4.4.2.3(a) and (b). The allowable stress is plotted against the effective slenderness ratio defined by Equation 3.11.2.3.

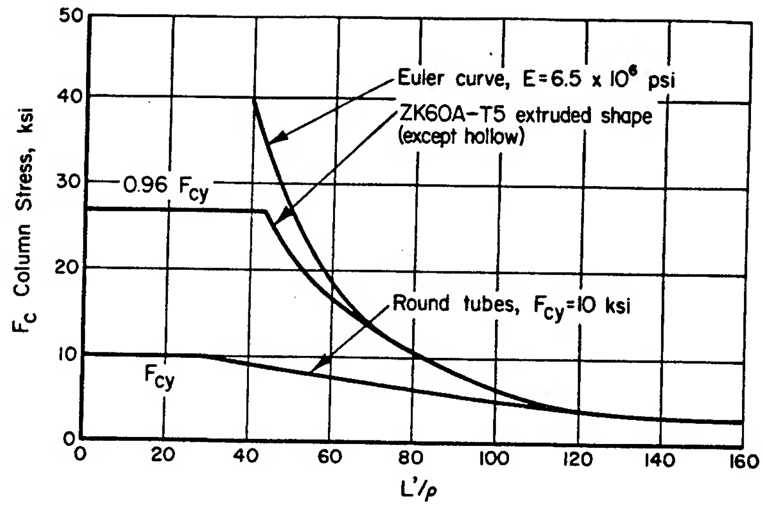

FIGURE 4.4.2.3(a). *Allowable column stresses for magnesium-alloy columns.*

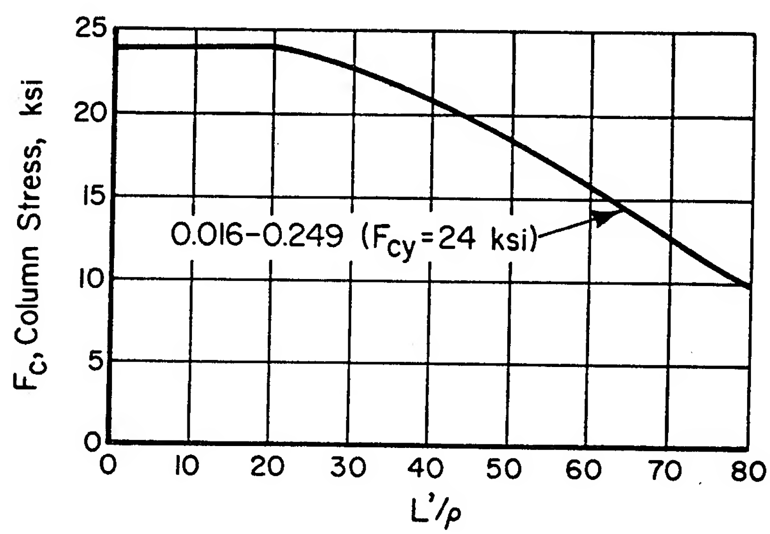

FIGURE 4.4.2.3(b). *Allowable column stresses for AZ31B-H24 magnesium-alloy sheet.*

4.4.3 TORSION

4.4.3.1 *General.*—The general statements relating to aluminum-alloy tubing in 3.11.3 are applicable to magnesium tubing.

4.4.3.2 *Torsion Properties.*—An empirical curve of the allowable torsional modulus of rupture for AZ62A-F magnesium-alloy round tubing (specification WW-T-825) is given in Figure 4.4.3.2.

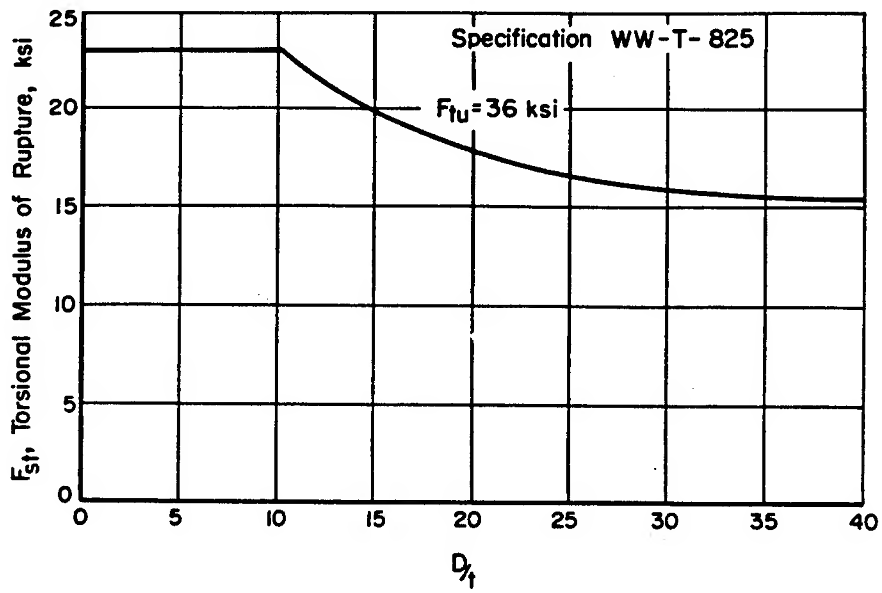

FIGURE 4.4.3.2. *Torsional modulus of rupture for AZ61A-F magnesium-alloy round tubing.*

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